

**High-resolution NU-WRF simulations of a deep convective-precipitation
system during MC3E: Part I: Comparisons between Goddard microphysics
schemes and observations**

Wei-Kuo Tao¹, Di Wu^{1,2}, Stephen Lang^{1,2}, Jiundar Chern^{1,3},
Christa Peters-Lidard⁴, Ann Fridlind⁵, and Toshihisa Matsui^{1,6}

¹*Mesoscale Atmospheric Processes Laboratory,*

NASA Goddard Space Flight Center, Greenbelt, MD

²*Science Systems and Applications, Inc., Lanham, MD*

³*Goddard Earth Sciences Technology and Research Program,*

Morgan State University, Baltimore, MD

⁴*Hydrological Sciences Laboratory,*

NASA Goddard Space Flight Center, Greenbelt, Maryland

⁵*NASA Goddard Institute for Space Studies, New York, NY*

⁶*Earth System Science Interdisciplinary Center*

University of Maryland, College Park, Maryland

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Corresponding author address: Dr. W.-K. Tao, Code 612,
Mesoscale Atmospheric Processes Laboratory, NASA/GSFC, Greenbelt, MD 20771

24 Email: Wei-Kuo.Tao-1@nasa.gov

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26 **Key Points**

- 27 • A new 4ICE microphysics scheme is implemented in a regional scale model.
- 28 • Radar reflectivities and rainfall intensities are sensitive to microphysics scheme.
- 29 • The 4ICE scheme shows improvements over 3ICE schemes with either
- 30 graupel or hail alone.

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Abstract

The Goddard microphysics scheme was recently improved by adding a 4th ice class (frozen drops/hail). This new 4ICE scheme was implemented and tested in the Goddard Cumulus Ensemble model (GCE) for an intense continental squall line and a moderate, less-organized continental case. Simulated peak radar reflectivity profiles were improved both in intensity and shape for both cases as were the overall reflectivity probability distributions versus observations. In this study, the new Goddard 4ICE scheme is implemented into the regional-scale NASA Unified - Weather Research and Forecasting model (NU-WRF) and tested on an intense mesoscale convective system that occurred during the Midlatitude Continental Convective Clouds Experiment (MC3E). The NU-WRF simulated radar reflectivities, rainfall intensities, and vertical and horizontal structure using the new 4ICE scheme agree as well as or significantly better with observations than when using previous versions of the Goddard 3ICE (graupel or hail) schemes. In the 4ICE scheme, the bin microphysics-based rain evaporation correction produces more erect convective cores, while modification of the unrealistic collection of ice by dry hail produces narrow and intense cores, allowing more slow-falling snow to be transported rearward. Together with a revised snow size mapping, the 4ICE scheme produces a more horizontally stratified trailing stratiform region with a broad, more coherent light rain area. In addition, the NU-WRF 4ICE simulated radar reflectivity distributions are consistent with and generally superior to those using the GCE due to the less restrictive open lateral boundaries.

Key words

55 Ice Microphysics, Severe rainfall, WRF

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1. Introduction

Many new and improved microphysical parameterization schemes have been developed over the past few decades [e.g., *Ferrier, 1994; Meyers et al., 1997; Reisner et al., 1998; Hong et al., 2004; Walko et al., 1995; Colle et al., 2004; Zhu and Zhang, 2004; Morrison et al., 2005; Straka and Mansell, 2005; Milbrandt and Yau, 2005; Morrison and Grabowski, 2008; Thompson et al., 2004, 2008; Dudhia et al., 2008, Morrison and Milbrandt, 2014, 2015; Morrison et al., 2015; and many others*]. Please see *Levin and Cotton [2008]* and *Tao and Moncrieff [2009]* for a review of the microphysics used in cloud-resolving models. In addition, please see Table 1 in *Tao et al. [2011a]* and *Lang et al. [2014]* for a brief review of microphysics parameterizations. They include one- and two-moment bulk schemes with two or more ice classes, three-moment bulk schemes, and spectral bin microphysics schemes. Different approaches have been used to examine the performance of new schemes. One approach is to examine the sensitivity of precipitation processes to different microphysical schemes. This approach can help to identify the strength(s) and/or weakness(es) of each scheme in an effort to improve their overall performance [e.g., *Ferrier et al., 1995; Straka and Mansell, 2005; Milbrandt and Yau, 2005*]. Idealized simulations have also been used to test new microphysical schemes by showing their behavior in a setting that is open to simpler interpretation. In addition, another approach has been to examine specific microphysical processes (e.g., turning melting/evaporation on or off, reducing the auto-conversion rate from cloud water to rain, etc.) within one particular microphysical scheme. This approach can help to identify the dominant microphysical processes within a particular scheme (i.e., evaporation, melting of large precipitating ice particles, etc.) responsible for determining

the organization and structure of convective systems [e.g., *Tao et al.*, 1995; *Wang*, 2002; *Colle et al.*, 2005; *Zhu and Zhang*, 2006a; and many others]. Table 1 lists the major characteristics for a range of previously published modeling papers in terms of model used, microphysics schemes (number of ice classes, number of moments), model resolution, integration time and case(s). This paper will apply the first approach to examine the performance of several different Goddard microphysical schemes.

Cloud-resolving models (CRMs) are typically run at horizontal grid spacing on the order of 1-2 km or finer and can simulate the dynamical and microphysical processes associated with deep, precipitating atmospheric convection. One advantage of using CRMs is that it allows for explicit interactions between cloud-microphysics, radiation and surface processes. Another advantage is that each model grid is either fully clear or cloudy, so that no cloud (maximum, random) overlap assumption is required.

Simulations using the Goddard Cumulus Ensemble (GCE) model with a new 4ICE (cloud ice, snow, graupel and hail) scheme for an intense squall line observed over central OK during the Midlatitude Continental Convective Clouds Experiment (MC3E) and loosely organized moderate convection observed over Amazonia during the Tropical Rainfall Measuring Mission Large-Scale Biosphere-Atmosphere Experiment in Amazonia (TRMM LBA) [*Lang et al.*, 2014] produced peak reflectivity profiles that were superior to previous iterations of the Goddard 3ICE graupel microphysics scheme [*Tao et al.*, 2003; *Lang et al.*, 2007, 2011] with peak intensities closer to the observed and that monotonically decreased with height also as observed. The 4ICE scheme was able to match the infrequent but relatively rare occurrence of intense echoes within the convective cores. Simulated reflectivity distributions versus height were also improved

105 versus radar in both cases compared to the earlier 3ICE versions. The main reason for
106 developing the 4ICE scheme was to expand the ability of the microphysics to include
107 more intense convection without the need to switch schemes (i.e., from 3ICE-graupel to
108 3ICE-hail) *a priori*. Furthermore, hail and graupel can occur in real weather events
109 simultaneously. Therefore, a 4ICE scheme (cloud ice, snow, graupel and hail) is useful
110 for numerical weather prediction, especially for high-resolution prediction of severe local
111 thunderstorms, mid-latitude squall lines and tornadoes. Current and future global high-
112 resolution CRMs need the ability to predict/simulate a variety of weather systems from
113 weak to intense (i.e., tropical cyclones, thunderstorms) over the entire globe; a 4ICE
114 scheme can respond appropriately to such a variety of environmental conditions.

115 GCE model simulations are typically forced with the observed large-scale
116 advective tendencies for temperature and water vapor using cyclic lateral boundary
117 conditions [i.e., *Tao et al.*, 2003; *Moncrieff et al.*, 1996] as was the case for the
118 simulations of the intense MC3E squall line in *Lang et al.* [2014]. The horizontally
119 uniform forcing and cyclic boundaries can influence the simulated spatial structures of
120 the squall line. Therefore, the performance of the 4ICE scheme needs to be further
121 assessed with different types of numerical models and initial/lateral boundary conditions.
122 Improved versions of the Goddard bulk microphysics with different options (3ICE and
123 4ICE) have been implemented into the NASA Unified - Weather Research and
124 Forecasting model (NU-WRF). The major objective of this study is to examine the
125 performance of these different Goddard schemes in terms of precipitation processes,
126 rainfall (including its intensity), the vertical distribution of cloud species, and in
127 comparison with observed radar profiles. Data collected during the joint NASA/DOE

MC3E field campaign will be used for this study. The paper has the following organization. Section 2 describes NU-WRF, changes to the Goddard microphysics, the MC3E case, and the numerical experiments. Section 3 presents the simulation results and their evaluation versus observations, and the summary and conclusions are given in section 4.

2. Model description

2.1 NU-WRF

Recently, several physical process parameterizations developed for NASA have been implemented into WRF to better represent/simulate cloud-aerosol-precipitation-land surface processes and interactions on satellite-resolvable scales (~1 km grid spacing). These parameterizations have been implemented into several WRF versions from 3.1.1 up through 3.5.1, collectively known as the NASA Unified - WRF or NU-WRF [Peters-Lidard *et al.*, 2014]. NU-WRF is available to non-NASA users. Several NASA physical packages (microphysics, radiation) have also been implemented into the NCAR ARW (Advanced Research WRF). These physical processes include CRM-based microphysics and radiation [Tao *et al.*, 2003; Lang *et al.*, 2007, 2011, 2014] that have been tested on convective systems in different environments, including a linear convective system in Oklahoma from the International H2O project (IHOP-2002) [Santanello *et al.*, 2009], an Atlantic hurricane (Hurricane Katrina from 2005) [Tao *et al.*, 2011a], high latitude snow events from the Canadian CloudSat CALIPSO Validation Project (C3VP) in 2007 [Shi *et al.*, 2010; Iguchi *et al.*, 2012a,b, 2014], a Pacific typhoon [Typhoon Morakot, 2009; Tao *et al.* 2011b], and mesoscale convective systems (MCSs) in Africa [Shi *et al.*, 2013] and

the Southern Great Plains (MC3E in 2011 [Tao et al., 2013]). In addition, two other major NASA modeling components have been coupled with NU-WRF representing land surfaces (i.e., the Land Information System (LIS) [Kumar et al., 2007]) and aerosols (i.e., the WRF Chemistry Model and Goddard Chemistry Aerosol Radiation and Transport Model (GOCART) [Chin et al., 2000, 2002, 2004]).

2.2 Goddard microphysics schemes

Several versions of the Goddard microphysics schemes have been implemented into NU-WRF. These schemes include the 3ICE scheme with graupel [Tao and Simpson, 1989, 1993; Lang et al., 2007, 2011], the 3ICE scheme with hail [McCumber et al., 1991; Tao et al., 2003], and the new 4ICE scheme with both graupel and hail [Lang et al., 2014]. Please see the Appendix for the details on these schemes as well as for the several further enhancements that have been made to the 4ICE scheme that were incorporated in this study.

2.3 Case

MC3E was a joint field campaign between the DOE ARM Climate Research Facility and NASA's Global Precipitation Measurement (GPM) mission Ground Validation (GV) program [Petersen et al., 2009]. It took place in central Oklahoma from 22 April to 6 June 2011. Some of its major objectives involve the use of high-resolution CRMs in precipitation science and include: (1) testing the fidelity of CRM simulations via intensive statistical comparisons between simulated and observed cloud properties and latent heating (LH) fields for a variety of case types, (2) establishing the limits of

CRM space-time integration capabilities for quantitative precipitation estimates, and (3) supporting the development and refinement of physically-based GPM microwave imager (GMI), dual-frequency precipitation radar (DPR), and DPR-GMI combined retrieval algorithms using ground-based observations, aircraft measurements, airborne radar and radiometer, and CRM simulations. The focus of this study will be the intense squall line case presented in *Lang et al.* [2014].

On 20 May 2011 a deep, upper-level low over the central Great Basin moved across the central and southern Rockies and into the central and northern Plains. A surface low pressure center in southeastern Colorado drew warm, moist air from the southern Plains to a warm front over Kansas, while a dry line extended southward from the Texas/Oklahoma Panhandle. As a result, several convective lines formed over the Great Plains and propagated eastward. The northern portion of a long convective line began to enter the MC3E sounding network around 07 UTC 20 May and by 09 UTC had merged with ongoing convection near the KS-OK border to form a more intense convective segment with a well-defined trailing stratiform region that then propagated through the network between 09 and 12 UTC. The convection along the leading edge of this intense squall line exited the network around 13 UTC leaving behind a large area of stratiform rain. For further details see *Lang et al.* [2014]. This case was also simulated with NU-WRF by *Tao et al.* [2013], but the focus was on the diurnal variation of precipitation.

2.4 Model set-up

Figure 1 shows the model grid configuration, which includes an outer domain and two inner-nested domains, having 9-, 3- and 1-km horizontal grid spacings with 524×380×61, 673×442×61, 790×535×61 grid points, respectively. Time steps of 18, 6 and 2 seconds were used in these nested grids, respectively. The Grell-Devenyi cumulus parameterization scheme [Grell and Devenyi, 2002] was used for the outer grid (9 km) only. For the inner two domains (3- and 1-km), the convective scheme was turned off. The PBL parameterization employed the Mellor-Yamada-Janjic [Mellor and Yamada, 1992] Level-2 turbulence closure model through the full range of atmospheric turbulent regimes. The scheme was coded/modified by Dr. Janjic for the NCEP Eta model.

The Goddard broadband two-stream (upward and downward fluxes) approach was used for the short- and long-wave radiative flux and atmospheric heating calculations [Chou and Suarez, 1999, 2001] and its explicit interactions with clouds (microphysics). Model terrain is smoothed from the 5-m (~5-km), 2-m (~4-km) and 30-second (~0.9 km) USGS terrain database for the three nested domains, respectively. Simulations start at 00 UTC 20 May 2014 for 48 hours of model integration. Initial conditions are from the GFS-FNL (Global Forecast System Final global gridded analysis [archive](#)) as are the lateral boundary conditions, which are updated every 6 hours.

2.5 Numerical experiments

Three numerical experiments are conducted for the MC3E case using various versions of the Goddard microphysics schemes: 3ICE-graupel [Lang *et al.*, 2011] termed “Graupel,” 3ICE-hail [McCumber *et al.* 1990; Tao *et al.* 2003] termed “Hail,” and the

new 4ICE scheme [Lang et al. 2014] with additional modifications termed “4ICE”.
Table 2 shows the list of numerical experiments performed for this case.

3. Results

3.1 Surface rainfall and its convective and stratiform characteristics

The National Mosaic and Multi-Sensor QPE (NMQ) system is a multiradar, multisensor system, ingesting base-level data from all available radars (NEXRAD, Canadian Radar, TDWR, gap radars) at any given time, performs quality control, and then combines reflectivity observations from individual radars onto a unified 3D Cartesian frame. Surface rainfall observation is from next generation quantitative precipitation estimation (Q2) radar-only product, which is a key component in NMQ system. Both their radar and precipitation data have a spatial and temporal resolution of 1 km and 5 min, respectively [Zhang et al., 2011].

The NU-WRF simulated rainfall for the three different Goddard microphysical schemes at 10 UTC on 20 May 2014 is shown in Fig. 2. All three NU-WRF simulations have a smaller light rain area in the stratiform region than was observed, though the combined coherence and intensity of the 4ICE simulation appears closer to the observed at the time shown (typical of other times). The observed convective system is a fast-propagating system. This feature is also generally captured by all three of the NU-WRF simulations (not shown). There are some notable differences between the simulations, however, which are well illustrated in Fig. 2. For the Graupel scheme, the area of heavy rainfall at the leading edge of the system appears smallest and narrowest. Though the Graupel scheme produces a broader, more coherent area of light to moderate rainfall than

the Hail scheme, such extensive areas of moderately intense rain were not observed. The areas of heavy rainfall in the Hail simulation are more robust than in the Graupel simulation but lack the coherent extended arc structure of the observations, the 4ICE scheme, and to some degree the Graupel scheme. The Hail scheme produces a smaller, less coherent light rain area than the other two schemes, but its intensity appears similar to that observed. In terms of the rainfall pattern, the 4ICE scheme agrees better overall with the observations than the other two simulations, with a convective leading edge that is more intense than the Graupel simulation and also longer and more coherent than the Hail simulation. The 4ICE trailing stratiform region also appears to match better with the observations, being deeper and more coherent than in the Hail simulation but remaining more uniform and not overly intense as in the Graupel simulation. Without hail, too much moderate-falling graupel is transported rearward in the Graupel simulation and does not fall out in the convective leading edge, whereas with the hail scheme, “dry collection” causes more of the slow-falling snow to be collected and fall out as hail in the convective leading edge. The 4ICE scheme modulates these biases by allowing only ice that was formed in a manner that would produce high particle density (e.g., freezing drops or extreme riming) to fall out as hail in the convective leading edge and therefore more slow-falling snow to be transported rearward to maintain a broader, more uniform light rain area.

Rainfall can also be separated into convective and stratiform regions. There are several reasons for making this distinction [Houze, 1997]. For example, precipitation rates are generally much higher in the convective region. Ice particles tend to be rimed in the convective region and to be aggregates in the stratiform region. Microphysics and, as

a consequence, surface rainfall and the vertical distribution of latent heating are also found to be different in these two regions [see the reviews by Houze, 1997 and Tao, 2003]. The convective-stratiform partitioning method used in this study is based on the horizontal radar reflectivity gradient [Steiner et al., 1995]. The criteria for identifying the convective region are based on intensity, “peakedness”, and the surrounding area as described by Steiner et al. [1995]. Because that scheme was originally developed for tropical convection, several input parameters for the partitioning scheme were tuned to fit mid-latitude scenarios [Feng et al., 2011]. A 2-km mean sea level (MSL) height (versus 3 km in Steiner et al. [1995]) is used as the analysis level in order to avoid bright band contamination, and the reflectivity threshold for the convective region is set to 43 dBZ (40 dBZ in Steiner et al. [1995]), according to the Z-R relationship in mid-latitudes. The rest of the echoes that exceed 10 dBZ, but are not identified as convective core, are designated as stratiform rain region [Feng et al., 2011] (See also *Lang et al.* [2004] for a review of convective and stratiform observational studies, modeling studies and different convective–stratiform separation methods.). The same convective-stratiform separation method is used for both the observations and model results.

Figure 3 illustrates typical similarities and differences between the observed and simulated convective and stratiform areas. As expected the convective regions in all three simulations (Figure 3b-d) are located at the leading edge of the convective system, consistent with NEXRAD data (Figure 3a; see section 3.3). The Graupel and 4ICE simulations produce a broad arc shape similar to that observed; the Hail scheme, however, only produces a small arc-shaped convective region over southern OK. All three simulations underestimate the stratiform rain area, though in terms of character, the

4ICE simulation is closest to the observations.

Tables 3 and 4 show the rainfall amount and area coverage quantitatively (at 1-km grid spacing) obtained from 06 UTC to 12 UTC on 20 May 2011. Data from the first 6 hours were not used since the simulations use a cold start. Both the modeled and observed convective systems are propagating squall lines, though the simulated convective lines propagate faster than observed and move out of the inner domain after 12 UTC. Only areas with rain rates greater than 0.15 mm/h, which is based on the Q2 minimum detectable rain rate, are partitioned. In the simulations, light rain regions (e.g. shallow cumulus or elevated anvil) that are not classified as either convective or stratiform region contribute to totals larger than the sum of the convective and stratiform parts. In addition, the partition scheme, which relies on 3D output, is applied every 10 min rather than every time step as in total accumulations. The results show that the rainfall amount in the 4ICE run is about 10% more than in the 3ICE runs (both Graupel and Hail), closest to that observed; however, its total rainfall is still underestimated by about 27% (Table 3). The model results from the previous study [Tao *et al.* 2013] also underestimated the total rainfall amount by about 26% (with 2-km grid spacing in the inner domain). Tao *et al.* [2013] conducted sensitivity tests on the surface processes and terrain height, but those did not result in an increase in total rainfall amount. Neither the improved microphysics nor the finer resolutions have much impact on the total amount rainfall. This underestimation is also shown in the runs with other WRF microphysics schemes (Part II) and sensitivity tests on surface fluxes and terrain height [Tao *et al.* 2013]. Initiating the model with clear skies (i.e., a cold start), the initial or boundary conditions, and the fact that the observed line extended farther south than the inner-most

domain could all be factors, but further study is needed to identify the reason(s) for this deficiency in the rainfall amount. The model simulated total rain coverage for all three simulations is also underestimated (Table 4) as the simulations fail to capture the complete extent of the observed stratiform rain area over western OK. This could be due to the real squall line extending further south than in the simulations, thereby boosting the development of the stratiform region at the southern end of the analysis domain relative to the simulations.

Tables 3 and 4 also show the observed and simulated rainfall amounts and area coverage in the convective and stratiform regions. All three simulations reproduce observed convective area coverage to within a factor of 0.8-1.2 times that observed, but all simulations also underestimate total convective rainfall by a factor of 0.3-0.5 or more; thus the simulated convective rain rates are weaker than observed on average. All three simulations also underestimate stratiform area coverage by a factor of roughly 0.4 while underestimating stratiform rainfall by a factor of 0-0.35; thus simulated stratiform rain rates tend to be more intense than observed. The Graupel simulation produces the most stratiform rain (~5 mm) and area (~15%); although rainfall amount is close to that observed, it is distributed over an appreciably smaller area than observed, indicating that typical stratiform rain rates are too intense. Consistent with previous modeling results, the Hail scheme produces less stratiform but more convective rain than the Graupel scheme. For example, McCumber *et al.* [1991] suggested that the most important characteristic difference between graupel and hail is the terminal velocity. For graupel, a smaller terminal velocity allows it to enter the stratiform (or behind the convective) region, where it becomes an important constituent of the stratiform region. The 4ICE

scheme produces roughly 30% more stratiform rainfall than the Hail scheme over roughly a 10% larger stratiform area, indicating that its overall stratiform rain is more intense. Stratiform rainfall accounts for about 53%, 35% and 39 % of the total rainfall in the Graupel, Hail and 4ICE schemes, respectively (Table 3). The Hail scheme yields a stratiform rain percentage of 35% in closest agreement with the observations but with rates and coverage that differ substantially from those observed; the 4ICE scheme stratiform rain percentage is only slightly higher, with similar biases. The 4ICE scheme has more convective rain in better agreement with the observations because it has a longer convective region owing to being better organized than the Hail scheme.

Figure 4a shows PDFs of the simulated and observed surface rainfall intensity. Both the 4ICE and Hail schemes have a higher proportion of heavy precipitation (i.e., > 30-40 mm/h) than the Graupel scheme. This is because larger hail falls quickly before melting to form large raindrops (and consequently high rain intensities). This result is in better agreement with observations than the Graupel scheme. In addition, the 4ICE and Hail schemes produce less moderate precipitation (i.e., 10-20 mm/h) than the Graupel scheme, which is also in better agreement with observations. However, the two schemes with hail still simulated less very heavy rainfall (i.e., > 40-50 mm/h) than was observed, though they are far superior to the Graupel scheme in this regard. Despite high temporal and spatial resolution, radar-only Q2 rainfall has its own limitations. As discussed in Tang et al. [2012], daily averaged rainfall from Q2 has a positive bias compared to gauge-corrected Stage IV and the NCEP Climate Prediction Center (CPC) rain gauge estimates during summer (JJA, 2010). However, it is uncertain as to how much of the positive bias is contributed from those grids with very heavy rain rates. The Hail scheme,

which has no graupel, generally simulated slightly more intense rainfall than the 4ICE scheme. The Graupel scheme generally produced more lighter and less intense precipitation (i.e., < 20-30 mm/h) compared to the Hail and 4ICE schemes as moderate-falling graupel is the dominant cloud species in the Graupel scheme. Rainfall PDFs for the convective region (Fig. 4b) are much flatter than the total but with similar biases; the Hail and 4ICE schemes are comparable to one another and somewhat underestimate the occurrence of rain rates above 40 mm/h whereas the Graupel scheme greatly underestimates their occurrence. Rainfall PDFs for the stratiform region (Fig. 4c) are much steeper than the convective. Overall, the Hail and 4ICE PDFs tend to agree well with the observed, having similar slopes while the Graupel rainfall PDF appears too steep, overestimating rates between 10 to 20 mm/h and underestimating those above 30 mm/h. The simulated rainfall intensity (heavy or light rainfall) can be important for hydrology and surface processes (e.g., hydrological as well as ocean mixed layer models).

3.2 *Hydrometeor properties*

Figure 5 shows vertical profiles of the horizontal domain- and time-averaged cloud species (i.e., cloud water, rain, cloud ice, snow, graupel and hail). The low-level rain and cloud water mixing ratios show little variation between the three schemes. Cloud ice, snow and graupel are dominant cloud species in the Graupel scheme (Figure 5a). The large snow and graupel amounts in the Graupel scheme lead to more moderate melting over a larger area and thus a large average rain mixing ratio immediately beneath the melting layer. The Graupel scheme produced a much larger graupel profile compared

to the 4ICE scheme, as both rimed particles and frozen drops are treated as graupel, which has a moderate fall speed and remains suspended much longer than hail. Hail has the fastest fall speeds, allowing it to fall further into the lower troposphere before fully melting as clearly shown in both the Hail and 4ICE schemes (Figures 5b and c). As in the Graupel scheme, snow is also a dominant cloud species in the Hail and 4ICE schemes. One major difference is that the Hail scheme has very little cloud ice compared to the Graupel and 4ICE schemes. The vertical distribution of snow and hail for the Hail scheme is quite similar to the results of Lin *et al.* [1983], which are also for a midlatitude thunderstorm, as it is mainly based on Lin *et al.* [1983].

Table 5 shows the domain- (vertical and horizontal) and time-averaged amounts of cloud species. The most abundant cloud species are cloud ice, snow and graupel in the Graupel scheme. Snow is the most abundant cloud specie in the Hail scheme, which also had very little cloud ice compared to the other two schemes. The Graupel scheme produced more cloud ice and snow than did the Hail scheme, as in earlier GCE model simulations [cf. McCumber *et al.*, 1991; Lang *et al.*, 2007, 2011]. For the 4ICE scheme, snow and cloud ice are the most abundant ice species. The Hail scheme has slightly more hail than the 4ICE scheme, which allows for graupel formation. All of the schemes simulated similar amounts of cloud water, rain, and total rainfall.

An accurate vertical distribution of cloud species is important for satellite retrievals [i.e., Lang *et al.*, 2007; Olson *et al.*, 2006]. Unrealistic precipitation ice contents (i.e., snow and graupel), for example, can bias the simulated brightness temperatures and make it difficult to infer cloud properties from remote sensing data, which link them with synthetic values from models [Matsui *et al.*, 2013].

Microphysics schemes vary in their representation of cloud processes, leading to differing amounts of hydrometeor types. Tables 6, 7 and 8 show the cloud species in the convective, stratiform, and cloudy (but not convective or stratiform) regions for the three Goddard schemes. For the Graupel scheme, snow and graupel are the most abundant hydrometeors in the both the convective and stratiform regions. The Hail scheme also has a relatively large amount of snow in both the convective and stratiform region, but the amounts are less than for the Graupel scheme. The Hail scheme has the largest amount of hail in the convective region. The large size and faster fall speed of hail causes it to melt at significantly lower levels than graupel, and the higher convective rain rate in the Hail simulation is mainly due to the presence of hail. The Hail scheme produces significantly less total precipitating ice and less rainfall than the Graupel and 4ICE schemes in the stratiform region. This is consistent with the rainfall amounts and stratiform percentages shown in Table 3. For the 4ICE scheme, the snow mass is also larger in the convective and stratiform regions compared to other cloud species but especially in the stratiform region. The Graupel scheme has more total precipitating ice (snow and graupel) than either the 4ICE (snow, graupel and hail) or Hail scheme in the stratiform region (Table 7), explaining its larger stratiform rain amount and percentage (Table 3).

Figures 6 and 7 show the vertical distribution of cloud species in the convective and stratiform regions. The main differences between the three Goddard schemes in the convective region are as follows: the Graupel scheme has more than twice as much cloud ice in the upper troposphere than the Hail scheme and more than twice as much graupel than the 4ICE scheme; the Hail scheme has more hail in the upper troposphere than the

4ICE scheme; and hail in the Hail and 4ICE schemes melts lower in the troposphere (penetrating to roughly 2 km) than does graupel in the Graupel scheme (penetrating to roughly 3 km). The Hail scheme has more hail below 4 km than the 4ICE, which is associated with high radar reflectivities as shown below. In the stratiform region, the Graupel scheme has more rain and consequently more rainfall (Table 3) than the Hail and 4ICE schemes. The Graupel scheme has much more graupel than 4ICE, which leads to more melting and therefore more rain as well as higher conditional rain rates in the stratiform region due to the higher proportion of faster falling graupel. However, snow is still the most abundant ice category in all three schemes, with the Hail scheme having the least amount and the 4ICE the most. The flux of snow particles through the melting layer may be comparable to that of graupel in the Graupel scheme due to its slower fall speed.

3.3 *Radar reflectivity*

As mentioned in section 3.1, gridded radar datasets were obtained from the NMQ system. Figure 8 shows time-height cross sections of the maximum reflectivity both observed by radar and simulated within the model domain for each of the three NU-WRF simulations from 06 to 12 UTC 20 May 2011. Simulated radar reflectivities are calculated from model rain, snow, graupel and hail contents assuming inverse exponential size distributions and accounting for all size and density mappings using the formulation of Smith et al. [1975] and Smith [1984]. Over this period within the analysis domain (Figure2), peak reflectivities associated with this intense squall line frequently exceeded 50 dBZ up to 10 km and 60 dBZ below about 7 km with 40 dBZ echoes

reaching as high as 15 km. The maximum reflectivities do show some fluctuation but overall the peak intensities are fairly steady (Figure 8a).

The model simulated maximum radar reflectivity is closely related to the largest precipitating particles in the convective region (Figure 6). The Graupel scheme (Figure 8b) significantly underestimates the peak 50 to 60 dBZ intensities of the observed squall line above the height of the freezing level due to the smaller size and lower density of graupel. The Hail scheme produces the highest reflectivities (Figure 8c) with peak values around 70 dBZ near 3-4 km and 55 dBZ values regularly reaching up to 12 km, which are somewhat more intense near the melting level and above 10 km than was observed for this case. These extreme dBZ values are mainly due to larger-sized hail as a result of the prescribed fixed low intercept value (i.e., 0.01 cm^{-4}) for hail. The Hail scheme also produces an unrealistic elevated minimum near 10 km. In contrast, the 4ICE simulation (Figure 8d) produces peak reflectivity values that decrease monotonically with height in best agreement with the observations, though the maximum intensities are somewhat underestimated below 8 km especially earlier in the period.

In addition to comparing the peak reflectivities, statistical comparisons in the form of contoured frequency with altitude diagrams (CFADs, see Yuter and Houze, [1995]) are performed to evaluate the overall performance of each simulation with respect to reflectivity. This technique computes the probability of a field as a function of height. To achieve the most meaningful comparisons, the CFADs must be computed as similarly as possible between the model and radar-derived fields. Comparisons between the model and observations are based on a 10 min temporal resolution for each.

Reflectivity CFADs were constructed by binning the reflectivities into 1-dBZ bins from 0 to 70 dBZ at each level.

Figure 9a shows the observed CFAD. The highest probabilities follow a coherent pattern with the peak density steadily decreasing with height from between 20 and 35 dBZ near the melting level to between 5 and 15 dBZ above 12 km, indicative of a robust sedimentation/aggregation effect. Maximum reflectivities at the lowest frequency contour of 0.001 % are just over 60 dBZ from the surface up to 6 km and drop off steadily aloft to around 45 dBZ at 14 km. The Graupel scheme simulated CFAD (Figure 9b) has some notable discrepancies with the observed (Figure 9a). First, the Graupel scheme lacks all of the reflectivity values higher than 45 dBZ above the freezing level. Second, although it captures some of the aggregation effect evident in the observed CFADs, it is too weak with too few echoes in the 20-25 dBZ range between 4 and 8 km.

The Hail scheme simulates high reflectivity values above the freezing level that are closer to the observed than the Graupel scheme. It produces peak reflectivity values at the lowest contour of ~65 dBZ near 4 km (melting level) that are about 5-8 dBZ higher than the other two schemes (Figure 9c). Observed peak reflectivities at this frequency are slightly over 61 dBZ. The Hail scheme also has an aggregation signature that deviates from the observed with the area of highest probabilities shifted too high (~30 to 35 dBZ) at midlevels and too low (< 10 dBZ) aloft. The 4ICE simulation, on the other hand, produces a more realistic radar reflectivity CFAD with a robust and coherent aggregation signature that much more closely resembles the observed. The 4ICE peak reflectivities are closer to the observed and monotonically decrease with height also as observed

(Figure 9a and d). Below the melting level, the 4ICE scheme maintains higher peak reflectivities due to melting hail in agreement with the observations.

Figure 10 shows the normalized degree of overlap between the observed and simulated PDFs at each level where unity represents perfect overlap and zero indicates no overlap between the observed and simulated reflectivity PDFs at a given level. The simulated 4ICE PDFs are consistently better than the Graupel between the surface and 12 km and vastly better than the Hail between 5 and 14 km. The Graupel scheme is superior to the Hail above the melting level but the reverse is true below. The Hail scheme has the lowest scores at mid-levels due to the shift in probabilities towards 30 to 35 dBZ values and the lowest scores aloft due to the shift towards weak values and having too broad of a distribution. Overall, the Hail scheme has the poorest overall performance in terms of CFADs, while the 4ICE clearly performs the best. Also, the 4ICE scores in NU-WRF are better than those using the GCE model for this case (see Figure 7 in *Lang et al.* 2014); this is likely due to the smaller domain and cyclic lateral boundaries used in the GCE model, which can inhibit the size and continuity of the stratiform region.

There is very high occurrence of low radar reflectivity values (5-25 dBZ) in the middle and upper troposphere (shown in red in Figures. 9a and d) and a low occurrence of high radar reflectivities (40-60 dBZ) above 3-4 km (shown in blue in Figures. 9a and d). Figure 11 shows the individual contribution of precipitating particles (rain, snow, graupel and hail) to the CFAD for the 4ICE simulation. Snow is largely responsible for the high occurrence of low dBZ values (Figure 11b, also see Figure 5c) and hail for the low occurrence of high dBZ values aloft (Figure 11d).

3.4 Cloud structure and vertical velocity

The observations show a classic continental uni-cellular squall line structure [Rutledge *et al.*, 1998; Johnson and Hamilton, 1988; see review by Houze, 1997] with deep, erect leading convective cell(s) followed by a wide trailing stratiform region (typical cross-section shown in Figure 12), which features a distinct high radar reflectivity bright band near the melting level separated from the convective core(s) by a transition area with a less prominent bright band.

The three NU-WRF model simulations also show a deep convective cell at the leading edge followed by a wide stratiform region (typical cross-sections shown in Figures 13, 14 and 15). However, there are several notable differences between the three schemes as well as various discrepancies with the observations. The Graupel scheme (Figure 13) produces a wider, more robust stratiform rain area than the Hail scheme (Figure 14), in better agreement with the observations, but its leading edge convection is much weaker than the other schemes as well as the observed. Compared to the Graupel scheme, the Hail scheme (Figure 14) produces stronger leading convective cells that are much more intense with high radar reflectivities above, at, and below the freezing level, in better agreement with the observations, though the leading edge cells appear to be too wide. However, the Hail scheme has a narrow and rather disjoint stratiform region wherein the highest reflectivities are elevated in the upper troposphere rather than near or below the melting layer as observed and simulated by the other schemes. These results are consistent with previous GCE modeling results for a tropical convective system [McCumber *et al.* [1991].

536 There are some notable improvements in the 4ICE-simulated structures (Figure
537 15) relative to the 3ICE schemes. First, in terms of the leading edge convection, the
538 simulated convective core(s) in the 4ICE scheme is more erect as observed due to the
539 inclusion of the rain evaporation correction [*Li et al.* 2009]. Also, it is both narrow and
540 intense similar to observed due to the inclusion of hail in conjunction with the elimination
541 of dry collection, whereas core intensities are too weak using the Graupel scheme and too
542 wide using the Hail scheme. Second, in terms of the trailing stratiform region, the 4ICE
543 scheme produces a broad, well developed stratiform rain area with radar reflectivity
544 values that closely match the observed and a pattern that is predominantly horizontally
545 stratified with higher values near and below the melting level. These features are in
546 much better agreement with the observations than the 3ICE schemes. The stratiform
547 region in the Graupel simulation is less horizontally stratified with more erect reflectivity
548 structures, while it is weaker and poorly organized as well as unrealistic with radar
549 echoes maximized in the upper troposphere in the Hail simulation. Finally, with the
550 inclusion of the snow breakup effect, snow sizes are kept small adjacent to the convective
551 core allowing the 4ICE scheme to capture some semblance of a transition region. The
552 observed stratiform region still covers a much larger area (~200 km) than do the
553 simulations (~75-125 km) though the Graupel and 4ICE schemes are superior to the Hail
554 scheme in this regard. All three schemes show that the convective updrafts are located at
555 the leading edge of the system above a pool of cold virtual potential temperature (Figs.
556 13-15, bottom panels). Overall, the 4ICE scheme captures more of the observed features
557 and has the most realistic structures among the three schemes.

Figure 16 shows CFADs of in-cloud vertical air velocity over the total, convective and stratiform regions, somewhat similar to those shown in *Tao et al.* [1987, their figure 10]. The general features are similar for all three simulations, with upward velocities exceeding 40 m/s in the mid-to-upper troposphere in the convective regions, peak convective updrafts about twice as strong as the downdrafts, and higher probabilities of moderate (~10 to 20 m/s) updrafts in the convective regions than in the stratiform. One notable difference between the three Goddard microphysics schemes is in the stratiform region where the PDFs for the Graupel scheme are appreciably wider than in the Hail and 4ICE schemes, meaning some of the more intense updrafts/downdrafts are being classified as stratiform. Another difference is in the convective region where the Graupel scheme has a higher percentage of weak-to-moderate updrafts (~5-10 m/s) in the lower troposphere but a reduced proportion aloft compared to other two schemes. The combination of more moderate reflectivity values and a more sheared updraft structure due to the lack of a rain evaporation correction makes it more difficult to cleanly separate the convective and stratiform regions in the Graupel simulation (Figure 3). This causes the low level updrafts to be included in the convective region but the upper portion of some of those updrafts, which are more tilted without the rain evaporation correction [cf. Li et al., 2009], to be assigned to the stratiform region. Overall, the fact that the total distributions are quite similar for all three schemes suggests that the larger scale shear and instability features dominate microphysics scheme differences in determining the updraft intensities and distribution, especially for such an unstable and sheared environment.

3.5 Comparision with previous results for the 20 May 2011 case

The 20 May 2011 MC3E case was one of the cases used to help develop and evaluate the new 4ICE scheme in *Lang et al.* [2014] using the GCE model. As was noted previously, those GCE model simulations were forced with observed large-scale advective tendencies for temperature and water vapor requiring the use of cyclic lateral boundary conditions, which can complicate and inhibit the simulated spatial structures of the squall line, namely the stratiform region, by allowing the leading edge convection to wrap around behind the MCS (see for example Figure 2 in *Lang et al.* [2014]). Restricting the stratiform area can affect the distribution of radar echoes and hence the agreement between the observed and simulated radar distributions. Accordingly, CFAD scores for the 4ICE scheme for this case in the GCE model study are consistently lower (i.e., less than 0.75; see Figure 7 in *Lang et al.* [2014]) than they are using NU-WRF in this study using the same original version of the 4ICE scheme (i.e., consistently above 0.8, Figure A4 or see Appendix). The ability to use a larger domain with open lateral boundaries and non-uniform horizontal forcing in NU-WRF is less restrictive and produces superior results and a more realistic evaluation of the 4ICE scheme.

Tao et al. [2013] examined the performance of NU-WRF for the real-time forecasts during MC3E. A post mission case study was also conducted for this May 20 case. The results suggest that propagating precipitation features and their associated cold-pool dynamics were an important physical process for the diurnal variation of precipitation. Model results also indicate that terrain effects are important during the initial stages of MCS development. On the other hand, surface fluxes and radiation processes only have a secondary effect for short-term simulations. There are differences

between *Tao et al.* [2013] and the current study in terms of model configuration (18, 6 and 2 km vs. 9, 3 and 1 km grid spacing) and initial conditions (North American Regional Reanalysis or NARR vs. Final Analysis by GFS or FNL). There are many similar results between the Graupel simulation in this study and *Tao et al.* [2013]. For example, the total rainfall is underestimated (see Table 5 in *Tao et al.* [2013]) as are the peak dBZ values above the melting level (see Figure 10 in *Tao et al.* [2013]), in part because the 3ICE scheme with graupel was also used in *Tao et al.* [2013]. The vertical structure is better in this study due at least in part to the higher horizontal resolution (see Figure 12 in *Tao et al.*, [2013]).

4. Summary

In this study, NU-WRF was used at a relatively high horizontal resolution (i.e., 1-km grid spacing for the innermost domain) to examine the performance of an improved version of the new Goddard 4ICE microphysics scheme in relation to two previous 3ICE versions of the Goddard microphysics (with hail and with graupel). An intense MCS that was observed during MC3E was selected for this study to examine the impact of the three Goddard microphysics schemes on the simulated precipitation processes associated with this intense convective event and to assess simulation performance based on observed radar and surface rainfall data. From a comparison of the three simulations with observations, the major highlights are as follows:

- All three microphysical schemes produced a fast-propagating system (though slightly too fast) with heavier rainfall at the leading edge of the convective system as was observed. However, the Graupel scheme produced less heavy rainfall at

627 the leading edge of system and more light to moderate rainfall in the trailing
628 stratiform region than the 4ICE and Hail schemes and observed. The Hail scheme
629 produced less light rainfall than the other two schemes and observed. All three
630 simulations underestimated the total rainfall amount and area coverage.

- 631 • In terms of the rainfall pattern, the 4ICE simulation agreed better with the
632 observations than the other two simulations, with a convective leading edge more
633 intense than in the Graupel simulation and longer and more coherent than in the
634 Hail simulation. The trailing stratiform region also better matched observations,
635 being more coherent than in the Hail simulation and more uniform and less
636 intense than in the Graupel simulation.
- 637 • Both the 4ICE and Hail schemes produced more heavy precipitation (i.e., > 30-40
638 mm/h) and less moderate precipitation (i.e., 10-20 mm/h) than the Graupel
639 scheme, in better agreement with observations.
- 640 • The 4ICE scheme captured both the rare occurrence of high radar reflectivity
641 values (~60 dBZ) above the freezing level and the common occurrence of low
642 radar reflectivity values (5-25 dBZ) in the middle and upper troposphere,
643 including a robust sedimentation/aggregation mode (Fig. 9) seen in the
644 observations. In contrast, the Graupel scheme failed to produce reflectivity values
645 higher than 45 dBZ above the freezing level, with too few echoes in the 20-25
646 dBZ range between 4 and 8 km. The Hail scheme did produce the infrequent but
647 high reflectivity values above the freezing level in fairly good agreement with the
648 observations, but produced a disjointed and weak reflectivity mode that was
649 unlike the robust aggregation mode in the observations.

- 650 • In the 4ICE scheme results snow is mainly responsible for the high occurrence of
651 low dBZ values in the middle and upper troposphere and hail the main contributor
652 for the low occurrence of very high dBZ values aloft.
- 653 • The 4ICE scheme produced erect, narrow and intense convective cores as
654 observed, whereas intensities were too weak in the Graupel cores and too wide in
655 the Hail cores.
- 656 • The 4ICE scheme also produced a broad, well-developed, more horizontally
657 stratified stratiform rain area with radar reflectivity values that most closely
658 matched those observed. The stratiform region in the Graupel simulation was less
659 horizontally stratified with more erect reflectivity structures, while in the Hail
660 simulation it was weaker and poorly organized with unrealistic with radar echoes
661 maximized in the upper troposphere.
- 662 • All three simulations contained strong convective updrafts located at the leading
663 edge of the system, and all three schemes produced similar PDFs of vertical
664 velocity, suggesting that the larger scale shear and instability are more important
665 than changes in the microphysics scheme for determining the updraft intensities
666 and distribution in this unstable and sheared environment.

667
668 The results indicated that overall the 4ICE simulation agreed better with the
669 observations in terms of rainfall intensity, radar reflectivity, and vertical and horizontal
670 structures than did the 3ICE simulations with graupel or hail. The results also confirmed
671 the importance of hail processes for this intense summertime convective system. Hail
672 can reproduce the intense echoes above 50 dBZ; without hail, too much moderate-falling

graupel is transported rearward in the Graupel simulation and does not fall out in the convective leading edge, whereas with the Hail scheme, “dry collection” causes some of the slow-falling snow to be collected and fall out as hail in the convective leading edge. The 4ICE scheme eliminates these biases by allowing only ice that was formed in a manner that would produce a high-density hydrometeor (e.g., freezing drops or extreme riming) to fall out as hail in the convective leading edge and therefore more slow-falling snow to be transported rearward to produce a broader more uniform light rain area. In addition, the evaporation correction (based on bin microphysics) helps keep the storm more upright. These results are consistent with those from the GCE model [Lang *et al.*, 2014]. In Part II, the Goddard 4ICE scheme will be compared with other WRF microphysics schemes (i.e., Morrison, WSM6, and WDM6). In addition, the Goddard 4ICE scheme will be implemented into the NCAR WRF for community use.

Simultaneously, the new 4ICE scheme has been implemented and tested in the Goddard Multi-scale Modeling System (MMF), which utilizes the GCE model as the cloud-precipitation parameterization within the Goddard Earth Observing System (GEOS) global model. The statistical distributions of convective precipitation type has been evaluated from the Goddard MMF by contrasting land and ocean regions in the Tropics in comparison with TRMM signal statistics (not shown). The Goddard MMF with the 4ICE scheme was able to realistically reproduce the more vigorous convective characteristics over land and the shallower, weaker characteristics over ocean. MMF-simulated microwave brightness temperatures show greater scattering signals over land than ocean similar to the TRMM Microwave Imager (TMI), suggesting more heavily rimed particles over land than ocean. This demonstrates the 4ICE scheme’s ability to

696 reproduce global statistics of land-ocean contrast in convective precipitation signals in
697 comparison with global observations. The study of different microphysical schemes from
698 the MMF shows that the new 4ICE scheme is superior to the Goddard 3ICE schemes in
699 producing realistic amounts and distributions of solid cloud and precipitating
700 hydrometeors when compared with three CloudSat/CALIPSO retrieval products (not
701 shown).
702

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1116 **Appendix: Description of the Goddard Microphysics schemes**

1117 The original Goddard two-class liquid and three-class ice microphysics scheme
 1118 developed and coded at Goddard [Tao and Simpson, 1993] was mainly based on Lin *et*
 1119 *al.* [1983] with additional processes from Rutledge and Hobbs [1984]. Modifications

were also made to better address saturation issues [Tao *et al.*, 2003]. This scheme has undergone several progressive revisions, culminating in an updated version of the 4ICE scheme currently used in this study. Details of these improvements are as follows.

(A.1) Lang et al. [2007] – 3ICE scheme

Lang *et al.* [2007] showed that eliminating dry collection by graupel in the Goddard 3ICE-graupel bulk microphysics scheme effectively reduced the unrealistic presence of graupel in the simulated anvil. However, comparisons with radar reflectivity data using CFADs revealed that the resulting snow contents were too large. The excessive snow was reduced primarily by lowering the collection efficiency of cloud water by snow and resulted in further agreement with the radar observations. The transfer of cloud-sized particles to precipitation-sized ice appeared to be too efficient in the original scheme. Overall, these changes to the microphysics lead to more realistic precipitation ice contents in the model and as a consequence more physically realistic hydrometeor profiles for radiance calculations for remote sensing applications.

(A.2) Lang et al. [2011] - 3ICE scheme

The performance of the GCE bulk microphysics scheme was further improved by reducing the bias in over penetrating 40-dBZ echoes at higher altitudes due mainly to excessively large contents and/or sizes of graupel particles at those altitudes [Lang *et al.*, 2011]. These improvements were achieved by systematically evaluating and improving individual ice processes, namely: (1) accounting for relative humidity and mean cloud ice mass in the Bergeron process for snow, (2) adding a simple Hallett-Mossop rime

splintering parameterization, (3) replacing the Fletcher curve, which determines the number of active ice nuclei (IN) as a function of temperature, with the Meyers *et al.* [1992] curve, which determines the active IN as a function of ice supersaturation, in the cloud ice nucleation, depositional growth and Bergeron growth parameterizations, (4) relaxing the saturation scheme to allow for ice supersaturation, (5) adding two additional parameterizations for contact nucleation and immersion freezing, (6) including cloud ice fall speeds, (7) allowing graupel and snow to sublime (the original Rutledge and Hobbs scheme only allows graupel and snow deposition but not sublimation, and (8) mapping the snow and graupel intercepts (effectively the mean snow and graupel particle diameters) as functions of temperature and mass. These changes also improved the overall model reflectivity probability distributions (i.e., CFADs).

(A.3) *Lang et al. [2014] – 4ICE scheme*

The Goddard Rutledge and Hobbs-based 3ICE scheme (cloud ice, snow and graupel) was then enhanced by the addition of hail processes and further modified to produce a new 4ICE scheme (cloud ice, snow, graupel, and hail) capable of simulating both intense and moderate convection. Hail processes taken from the 3ICE-hail scheme based on Lin et al. [1983] included hail riming, accretion of rain, deposition/sublimation, melting, shedding and wet growth. Hail dry collection was eliminated to prevent the same excessive buildup of hail as had occurred previously with graupel [Lang et al., 2007]; however, hail near wet growth is allowed to efficiently collect other ice particles. Processes that freeze rain now initiate hail (high density ice) not graupel. Four new hail processes were added: wet hail accretion of graupel, rime splintering via hail riming, hail

conversion to snow via deposition at colder temperatures (also applied to graupel), and hail conversion to graupel due to riming under non wet growth conditions. Besides the hail processes, further modifications were made to the 3ICE processes, including allowing greater ice supersaturation and mitigating spurious evaporation/sublimation in the saturation adjustment scheme and the inclusion of a bin microphysics-based [Li et al., 2009] rain evaporation correction but with physical raindrop size constraints and a vapor diffusivity factor. The improved 3ICE snow/graupel size-mapping schemes were adjusted to be more stable at higher mixing ratios and to increase the aggregation effect for snow. A snow density mapping [Brandes et al., 2007] was also added. The resulting 4ICE scheme was shown to perform well not only for the intense MC3E 20 May squall line case presented in this study but also for less organized moderate convection observed during TRMM LBA. Not only were the 4ICE radar CFADs as good or better than the previous 3ICE versions, but peak reflectivity profiles for the moderate case were actually superior to the 3ICE in overall intensity despite the addition of a frozen drops/hail category by realistically decreasing monotonically with height above the freezing level as observed due to the greater fall speeds, which allowed higher density precipitation ice to remain near the freezing level.

(A.4) Additional modifications to the 4ICE scheme

Several additional modifications have now been added to further improve the flexibility and performance of the 4ICE scheme. First, ice supersaturations on the order of tens of percent are commonly observed [Jensen et al., 2001; Stith et al., 2002; Garrett et al., 2005]; however, average ice supersaturations are much lower. The peak ice

1189 supersaturation was increased to allow up to 20% in the 4ICE scheme but was applied
1190 everywhere, resulting in a weaker convective system overall. The new formulation
1191 allows for a background supersaturation of 5%, which increases linearly up to a
1192 maximum of 21% as the updraft intensity increases above a background value of 2 m/s.
1193 Second, the autoconversion of cloud ice to snow (P_{saut}) follows a Kessler formulation
1194 where a threshold amount (i.e., of ice) must be exceeded before the excess is converted to
1195 in this case snow based on a specified timescale and efficiency. The previous
1196 configuration for P_{saut} was quite weak and although strengthened in 4ICE still appeared
1197 too weak and contributes to having a patchy anvil. Lowering the threshold from 0.6 g m^{-3}
1198 to 0.06 g m^{-3} improves the homogeneity of the simulated anvils. The Meyers *et al.*
1199 [1992] curve for the number of active IN was replaced by the Cooper curve [Cooper,
1200 1986]. Being a single moment scheme, the previous ice number concentration is not
1201 stored, which, using the Meyers curve, results in the number of IN decreasing as excess
1202 vapor is absorbed. In conjunction with this change, the IN number concentration is
1203 constrained such that the mean ice particle size cannot exceed the specified minimum
1204 snow size (i.e., 100 microns).

1205 Next, the snow mapping scheme was reconfigured to account for the effects of
1206 snow breakup via interactions with graupel and hail. Although dry collection is turned
1207 off in 4ICE such that graupel and hail do not collect snow, their interaction can affect the
1208 distribution of snow particle sizes. Over the years a lot of effort [e.g., Hallett and
1209 Mossop, 1974; Hobb and Rangno, 1985; Oraltay and Hallett, 1989] has been devoted to
1210 explaining the mechanisms by which ice crystal concentrations can be observed well in
1211 excess of the background IN concentration [e.g., Mossop et al., 1968, 1972; Hobbs, 1969,

1974]. These secondary ice multiplication studies have focused primarily on the enhancement of ice crystal concentrations. Less research has been done in the area of mechanical ice breakup via ice-ice collisions [Yano and Phillips, 2011] and very little regarding the impact on the larger parent particles. In addition to the potential for interactions between various sizes of snow particles themselves to produce a self-limiting snow size distribution [Lo and Passarelli, 1982], larger aggregates are unlikely to coexist with faster falling graupel or hail particles as they would likely breakup as a result of such collisions. Vardiman [1978] performed early laboratory measurements of ice fragmentation and demonstrated the potential efficacy of mechanical fracturing especially of rimed dendrites by graupel. Griggs and Choularton [1986] also conducted a laboratory study on ice fragmentation and reported that vapor-grown dendrites are fragile and that their collision with graupel could produce a substantial number of ice crystals.

Using the laboratory data of Takahashi et al. [1995], Yano and Phillips [2011] constructed an idealized model to demonstrate that mechanical break up due to ice-ice collisions involving graupel can substantially contribute to the ice multiplication effect. Though these studies again focused on the production of ice fragments, it is apparent that such collisions would have an impact on the parent snow particle sizes. The snow mapping scheme that was carried over and modified in the 4ICE scheme has been further modified to allow a more robust aggregation effect in the absence of graupel and hail. However, when graupel and/or hail are present, a simple scaling (S_{hgx}) based on the local graupel/hail mixing ratio(s) is used to increase the snow intercept obtained from the mapping scheme to reduce snow particle size where:

$$S_{\text{hgx}} = \max(1, q_h \times 125.) + \max(1, q_g \times 25.) \quad \text{when } q_h > 0.008 \text{ g m}^{-3}, q_g > 0.04 \text{ g m}^{-3}$$

and q_h and q_g are the hail and graupel mixing ratios, respectively. This formulation produces convective snow sizes that remain small but allows anvil snow sizes to become large using a common snow mapping and thus improve the effective mapping in each region rather utilize a single compromise mapping for both.

Finally, a simple hail-mapping scheme was introduced. Lang et al. [2014] demonstrated the performance of the 4ICE scheme for both moderate and intense convection; however, because the scheme still retained the use of a fixed intercept, a series of experiments was conducted for each case using different hail intercepts (i.e., equivalent to smaller-, medium-, and larger-sized hail). It was found that smaller hail performed the best for the moderate case, while medium hail performed best for the intense. As noted in Lang et al. [2014], it is not optimal to have to choose the hail intercept for each case *a priori*. Therefore, a simple hail mapping scheme has been devised based on the peak hail profiles from the moderate and intense cases in the Lang et al. [2014] study. In the mapping, a starting intercept appropriate for smaller hail (i.e., 0.240 cm^{-4}) is scaled down (i.e., hail size increases) as hail mixing ratio increases beyond a minimum threshold. It then reaches a minimum value (i.e., 0.0048 cm^{-4}) upon reaching a maximum threshold beyond which it no longer changes. The two thresholds are shown as a function of the local (i.e., in cloud not environmental) temperature in Figure A1.

Figures A2 and A3 show some of the differences between the original 4ICE scheme (Figure A2) in Lang et al. [2014] and the 4ICE scheme with the additional improvements made for this study (Figure A3). Both schemes feature erect leading edge

1258 convective cores, but the current scheme has more of a transition region between the
1259 erect core and the trailing stratiform are due to the snow break up effect. Its stratiform
1260 features are also more horizontally stratified due to the associated change in the snow
1261 mapping, which appears to better match the observed stratiform structure, which is also
1262 quite horizontally stratified. Figure A4 shows that the current 4ICE scheme has slightly
1263 better CFAD score at most levels.

1264

1265 LIST OF TABLES

1266 Table 1: Key papers using high-resolution numerical cloud models with bulk
1267 microphysics schemes to study the impact of microphysical schemes on
1268 precipitation. Model type (2D or 3D), microphysical scheme (one moment or
1269 multi-moment), resolution (km), number of vertical layers, time step
1270 (seconds), case and integration time (hours) are all listed. Papers with a “*”
1271 are used for comparison with the present study, papers with a “#” denote
1272 development of a new scheme, papers with a “\$” modify/improve existing
1273 schemes, papers with a “&” compare different schemes, and papers with a
1274 “%” indicate process (budget) studies. TCM3 stands for the “Tropical
1275 Cyclone Model with triple nested movable mesh”.

1276 Table 2 List of numerical experiments.

1277 Table 3 Total rainfall and its convective and stratiform components from observations
1278 and NU-WRF simulations for three different microphysical schemes.

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1280 mm/h) and its convective and stratiform components from observations and
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1282 Table 5 Domain averaged hydrometeor mixing ratios for three different microphysics
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1285 three different microphysics schemes, units in mm.

1286 Table 7 Domain averaged hydrometeor mixing ratios in the stratiform region for three
1287 different microphysics schemes, units in mm.

1288 Table 8 Domain averaged hydrometeor mixing ratios in the cloudy (but not
1289 convective or stratiform) region for three different microphysics schemes,
1290 units in mm.

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1292

| | <i>Model</i> | <i>Microphysics</i> | <i>Resolutions</i> <i>Vertical Layers</i> | <i>Integration</i> <i>Time</i> | <i>Case</i> |
|---|----------------------|--|--|-----------------------------------|----------------------------------|
| Lin <i>et al.</i> (1983) | 2D | 3-ICE | 200 m/95 | 48 min | Montana Hail Event |
| Cotton <i>et al.</i> (1982, 1986) | 2D | 3-ICE & Ni | 500 m/31 | 5 hours | Orographic Snow |
| Rutledge and Hobbs (1984) | 2D kinematic | 3-ICE | 600 m/20 | Steady State | Narrow Cold Front |
| Lord <i>et al.</i> (1984) * | 2D axisymmetric | 3-ICE vs Warm Rain | 2 km/20 | 4.5 days | Idealized |
| Yoshizaki (1986)# | 2D slab-symmetric | 3-ICE scheme vs Warm Rain | 0.5 km/32 | 4.5 hours | 12 September GATE Squall Line |
| Nicholls (1987) | 2D slab-symmetric | 3-ICE vs Warm Rain | 0.5 km/25 | 5 hours | 12 September GATE Squall Line |
| Fovell and Ogura (1988)#% | 2D slab-symmetric | 3-ICE vs Warm Rain | 1 km/31 | 10 hours | Mid-latitude Squall Line |
| Tao and Simpson (1989, 1993)# | 2D and 3D | 3-ICE vs Warm Rain | 1 km/31 | 12 hours | GATE Squall Line |
| Tao <i>et al.</i> (1990) | 2D | 3-ICE | 1 km/31 | 12 hours | GATE Squall Line |
| McCumber <i>et al.</i> (1991)%\$ | 2D and 3D | 3-ICE scheme (graupel vs hail, 2ICE vs 3ICE) | 1 km/31 | 12 hours | GATE Squall Line |
| Wu <i>et al.</i> (1999) | 2D slab-symmetric | 2 ICE | 3 km/52 | 39 days | TOGA COARE |
| Ferrier (1994), Ferrier <i>et al.</i> (1995)# | 2D slab-symmetric | 2-moment 4-ICE | 1 km/31 | 12 hours | COHMEX, GATE Squall Line |
| Tao <i>et al.</i> (1995) | 2D slab-symmetric | 3-ICE | 0.75 and 1 km/31 | 12 hours | EMEX, PRESTORM |
| Walko <i>et al.</i> (1995)# | 2D | 4-ICE | 0.3 km/80 | 30 min | Idealized |
| Meyers <i>et al.</i> (1997)#\$ | 2D | 2-moment 4-ICE | 0.5 km/80 | 30 min | Idealized |
| Straka and Mansell (2005)# | 3D | 10-ICE | 0.5 km/30 | ~2 hours | Idealized |
| Lang <i>et al.</i> (2007)\$ | 3D | 3-ICE | 0.25 to 1km /41 | 8 hours | LBA |

| | | | | | |
|---------------------------------------|----------------------------|---------------------------------|----------------------------------|--------------------------|--------------------------------------|
| Zeng <i>et al.</i> (2008)\$ | 2D and 3D | 3-ICE | 1 km/41 | 40 days | SCSMEX, KWAJEX |
| Milbrandt and Yau (2005)# | 1D | Three-moment | /51 | 50 minutes | Idealized Hail Storm |
| Morrison <i>et al.</i> (2005)# | Single column model | Two moments and 2-ICE | Single column model 27 layers | 3 days | SHEBA FIRE-FACE |
| Morrison and Grabowski (2008)# | 2D | Two-moment ICE | 50 m/60 | 90 minutes | Idealized |
| Reisner <i>et al.</i> (1998)# | MM5 Non-hydrostatic | 3-ICE and 2- moment for ICE | 2.2 km/27 | 6 hours (2.2 km grid) | Winter Storms |
| Thompson <i>et al.</i> (2004)# | MM5 2D | 3-ICE | 10 km/39 | 3 hours | Idealized |
| Thompson <i>et al.</i> (2008)\$ | WRF 2D | 3-ICE | 10 km/39 | 6 hours | Idealized |
| Colle and Mass (2000) | MM5 Non-hydrostatic | 3-ICE | 1.33 km/38 | 96 hours | Orographic Flooding |
| Colle and Zeng (2004)% | 2-D MM5 Non-hydrostatic | 3-ICE | 1.33 km/39 | 12 hours | Orographic |
| Colle <i>et al.</i> (2005)% | MM5 Non-hydrostatic | 3-ICE | 1.33 km/320 | 36 hours | IMPROVE |
| Yang and Ching (2005)* | MM5 Non-hydrostatic | 3-ICE | 6.67 km/23 | 2.5 days | Typhoon Toraji (2001) |
| Zhu and Zhang (2006b)* | MM5 Non-hydrostatic | 3-ICE | 4 km/24 | 5 days | Bonnie (1998) |
| Wang (2002)* | TCM3-hydrostatic | 3-ICE | 5 km/21 | 5 days | Idealized |
| Hong <i>et al.</i> (2004)# | WRF Non-hydrostatic | 3-ICE | 45 km/23 | 48 hours | Korean Heavy Rainfall event |
| Li and Pu (2008)* | WRF Non-hydrostatic | 2-ICE and 3-ICE | 3 km/31 | 1.25 days | Hurricane Emily (2005) |
| Jankov <i>et al.</i> (2005; 2007)* | WRF Non-hydrostatic | 2-ICE and 3ICE | 12 km/31 | 1 day | IHOP |
| Dudhia <i>et al.</i> (2008)*** | WRF Non-hydrostatic | 3-ICE | 5 km/31 | 1.5 days | Korean Heavy Snow event |
| Tao <i>et al.</i> (2009, 2011) | WRF Non-hydrostatic | 2-ICE and 3ICE 3ICE and 4ICE | 1 km/41 1.667 km/31 | 1.5 days 3 days | IHOP and Hurricane Katrina (2005) |

| | | | | | |
|--|------------------------------|-------------------------------------|-------------------------------|-----------------------|--|
| Han <i>et al.</i> (2012)& | WRF Non-hydrostatic | 1- and 2-moment for 3ICE | 1.3 km/52 | 2 days | Winter cyclone in northern california |
| Iguchi <i>et al.</i> (2012a,b) | WRF Non-hydrostatic | SBM for 4ICE | 1 km/60 | 36 h | C3VP and MC3E |
| Li <i>et al.</i> (2009a,b)& | 2D | Bulk and SBM | 1 km/33 | 12 h | PRE-STORM |
| Del Genio <i>et al.</i> (2012) | WRF Non-hydrostatic | 2-moment for 3ICE | 600 m/50 | 3 days | TWP-ICE |
| Gilmore <i>et al.</i> (2004)\$ | SAM | 1-moment for 3ICE | 1 km/ 40 | 2 h | Idealized |
| Hong <i>et al.</i> (2003)# | WRF Non-hydrostatic | 1-moment for 3ICE | 2D: 250 m/ 80 3D: 45 km/23 | 2D: 1 h 3D: 2 days | 2D Idealized 3D |
| Powell <i>et al.</i> (2012)& | WRF Non-hydrostatic | 1- and 2-moment for 3ICE | 3 km/61 | 24h and 30h | AMMA |
| Tao <i>et al.</i> (2013)\$ | WRF Non-hydrostatic | 3ICE | 2 km/ 41 | 2 days | MC3E |
| Wu <i>et al.</i> (2013)& | WRF Non-hydrostatic | 2-ICE and 3ICE | 3 km/ 41 | 2 days | SGP MCSs |
| Lang <i>et al.</i> (2011)\$ | GCE 3D | 3ICE | 250, 500 m/70 | 1 day and 72 h | TRMM LBA and KWAJEX |
| Morrison <i>et al.</i> (2008)& | WRF 2D | 1- and 2-moment for 3ICE | 250 m/? | 7 h | Idealized |
| Varble <i>et al.</i> (2011)& | DHARMA, UKMO, MESONH, SAM | 1- and 2-moment for 3ICE | 917 m and 1 km/ 50 or 120 | 16 days | TWP-ICE |
| Fridlind <i>et al.</i> (2012)& | Multi-models | 1- and 2-moment for 2ICE or 3ICE | 900m-3km/100- 1000m | 6 days | TWP-ICE |
| Van Weverberg <i>et al.</i> (2012)\$ | ARPS | 1-moment 3ICE | 3km/50 | 30 h | Convective and stratiform cases |
| Van Weverberg <i>et al.</i> (2012)& | WRF 2D | 2-moment for 3ICE, 4ICE | 1 km/ 250m 1 km/40 | 5 h | Idealized |
| Van Weverberg <i>et al.</i> (2013a,b) | WRF 3D | 2-moment for 3ICE | 1km/40 | 5h | Idealized and TWP |
| Van Weverberg <i>et al.</i> (2013)& | WRF Non-hydrostatic | 1- and 2-moment for 2ICE or 3ICE | 4km/35 | 7 days | TWP |
| Bryan and Morrison | CM1 | 1- and 2-moment | 250m/100 | 9 h | Idealized |

| | | | | | |
|-----------------------------------|------------------------------------|--|---------------------------|----------|---------------------------------|
| (2011)& | 3D | for 3ICE | | | |
| Morrison and Milbrandt (2011)& | WRF 3D | 2- moment for 3ICE and 4ICE | 1km/500m | 2 h | Idealized |
| Morrison and Grabowski (2007)& | 2D kinematic modeling framework | Bulk 2-moment and bin/warm rain | NAN | NAN | Idealized |
| Luo <i>et al.</i> (2010)\$& | WRF Non-hydrostatic | 1- and 2-moment for 3ICE | 3.3 km/30 | 1 day | Mei-Yu front |
| Li <i>et al.</i> (2008) | WRF 3D with 3DVAR | 1-moment 3ICE | 27, 9, 3 km/31 | 30 hours | Hurricane Emily |
| Molthan and Colle (2012) | WRF | 1- and 2-moment 3ICE | 9, 3, 1 km/34 | 1 case | C3VP synoptic snow |
| Guy <i>et al.</i> (2013) | GCE 3D | 1-moment 3ICE | 1 km / 63 | 2 cases | AMMA WAM/AEW Sahel |
| Lang <i>et al.</i> (2014) | GCE 3D | 1-moment 3ICE and 4ICE | 200 m – 1 km / 70 - 76 | 6 – 96 h | TRMM LBA and MC3E convection |
| Morrison and Milbrandt (2015)# | WRF 2D | 1-moment Predicted particle properties or P3 | 1 km/80 | 6 h | Idealized |
| Morrison <i>et al.</i> (2015)& | WRF | P3 and 3ICE | 1 km/100 | 6 h | Oklahoma squall line |

1293

1294 Table 1 Key papers using high-resolution numerical cloud models with bulk microphysics
1295 schemes to study the impact of microphysical schemes on precipitation. Model type
1296 (2D or 3D), microphysical scheme (one moment or multi-moment), resolution (km),
1297 number of vertical layers, time step (seconds), case and integration time (hours) are all
1298 listed. Papers with a “*” are used for comparison with the present study, papers with a
1299 “#” denote development of a new scheme, papers with a “\$” modify/improve existing
1300 schemes, papers with a “&” compare different schemes, and papers with a “%” indicate
1301 process (budget) studies. TCM3 stands for the “Tropical Cyclone Model with triple
1302 nested movable mesh”.

1303

1304

| Run | Microphysics |
|---------|--------------------------------------|
| Graupel | As Tao et al. (2013) except for 1 km |
| Hail | 1 km with 3ICE - hail option |
| 4ICE | 1 km with updated 4ICE |

1305

1306 Table 2 List of numerical experiments.

1307

1308

1309

| | Total Rainfall (mm) | Convective Rainfall (mm) | Stratiform Rainfall (mm) | Stratiform % |
|-------------|------------------------|-----------------------------|-----------------------------|--------------|
| Observation | 14.12 | 8.66 | 4.94 | 35.01 |
| Graupel | 9.31 | 3.86 | 4.90 | 52.65 |
| Hail | 9.38 | 5.59 | 3.27 | 34.87 |
| 4ICE | 10.30 | 5.83 | 4.02 | 39.05 |

1310

1311 Table 3 Total rainfall and its convective and stratiform components from observations
1312 and NU-WRF simulations for three different microphysical schemes.

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1316

| Run | Total Rainfall Area Coverage in % | Convective Area Coverage in % | Stratiform Aera Coverage in % |
|-------------|--------------------------------------|----------------------------------|----------------------------------|
| Observation | 46.51 | 4.50 | 24.03 |
| Graupel | 25.09 | 5.01 | 15.39 |
| Hail | 25.64 | 4.40 | 13.68 |
| 4ICE | 23.99 | 5.13 | 14.98 |

1317

1318 Table 4 Total rainfall coverage (for rain rates greater than the Q2 minimum of 0.15
1319 mm/h) and its convective and stratiform components from observations and
1320 NU-WRF simulations for three different microphysical schemes.

1321

| | Cloud Water | Rain | Cloud Ice | Snow | Graupel | Hail |
|---------|----------------|-------|--------------|-------|---------|-------|
| Graupel | 0.218 | 0.288 | 0.534 | 1.439 | 0.706 | N/A |
| Hail | 0.198 | 0.222 | 0.099 | 0.810 | N/A | 0.155 |
| 4ICE | 0.190 | 0.291 | 0.314 | 1.608 | 0.185 | 0.124 |

1322

1323 Table 5 Domain averaged hydrometeor mixing ratios for three different microphysics
1324 schemes, units in mm.

1325

| | Cloud Water | Rain | Cloud Ice | Snow | Graupel | Hail |
|---------|----------------|-------|--------------|-------|---------|-------|
| Graupel | 0.076 | 0.151 | 0.108 | 0.273 | 0.240 | N/A |
| Hail | 0.063 | 0.159 | 0.027 | 0.161 | N/A | 0.117 |
| 4ICE | 0.075 | 0.186 | 0.100 | 0.284 | 0.067 | 0.101 |

1326

1327 Table 6 Domain averaged hydrometeor mixing ratios in the convective region for
1328 three different microphysics schemes, units in mm.

1329

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1331

1332

1333

| | Cloud Water | Rain | Cloud Ice | Snow | Graupel | Hail |
|---------|----------------|-------|--------------|-------|---------|-------|
| Graupel | 0.058 | 0.133 | 0.197 | 0.823 | 0.388 | N/A |
| Hail | 0.048 | 0.059 | 0.032 | 0.529 | N/A | 0.036 |
| 4ICE | 0.042 | 0.101 | 0.120 | 0.982 | 0.100 | 0.021 |

1334

1335 Table 7 Domain averaged hydrometeor mixing ratios in the stratiform region for three
1336 different microphysics schemes, units in mm.

| | Cloud Water | Rain | Cloud Ice | Snow | Graupel | Hail |
|---------|----------------|-------|--------------|-------|---------|-------|
| Graupel | 0.084 | 0.004 | 0.229 | 0.343 | 0.078 | N/A |
| Hail | 0.087 | 0.004 | 0.040 | 0.120 | N/A | 0.002 |
| 4ICE | 0.073 | 0.004 | 0.094 | 0.342 | 0.018 | 0.002 |

1337

1338 Table 8 Domain averaged hydrometeor mixing ratios in the cloudy (but not
1339 convective or stratiform) region for three different microphysics schemes,
1340 units in mm.

1341

1342 LIST OF FIGURES

1343 Figure 1 NU-WRF grid configuration. The outer domain (labeled 1 at the center) has a
1344 horizontal resolution of 9 km. The middle domain (labeled 2) has a horizontal
1345 resolution of 3 km, and the inner domain (labeled 3) has a horizontal resolution
1346 of 1 km and covers the southern Plains.

1347 Figure 2 Surface one hour accumulated rainfall from (a) Q2 radar-only and the (b)
1348 Graupel, (c) Hail, and (d) 4ICE NU-WRF simulations ending at 10 UTC on 20
1349 May 2011. The precipitation analysis area is indicated by the red boundary.

1350 Figure 3 Observed and NU-WRF simulated convective and stratiform areas at 10 UTC
1351 on 20 May 2011. Red indicates convective regions and green stratiform
1352 regions.

1353 Figure 4 PDFs (probability distribution functions) of observed and NU-WRF simulated
1354 rainfall intensity in mm h^{-1} from three different microphysical schemes. The
1355 observed rain rates are from Q2. PDFs were calculated every 10 minutes from
1356 both observed and simulated datasets from 06 UTC to 12 UTC on 20 May
1357 2011 within the analysis domains shown in Figure 2.

1358 Figure 5 Hydrometeor profiles from the (a) Graupel, (b) Hail, and (c) 4ICE schemes
1359 from 06 UTC to 12 UTC on 20 May 2011.

1360 Figure 6 Same as Figure 5 except for the convective regions.

1361 Figure 7 Same as Figure 5 except for the stratiform regions.

1362 Figure 8 Maximum radar reflectivities for (a) NEXRAD observations and NU-WRF
1363 simulations with the (b) Graupel, (c) Hail, (d) 4ICE microphysics schemes.

1364 Right axes are heights in km, while horizontal lines show the time range from
1365 00 UTC to 12 UTC on 20 May 2011.

1366 Figure 9 Radar reflectivity CFADs from (a) NEXRAD observations and NU-WRF
1367 simulations with the (b) Graupel, (c) Hail, (d) 4ICE microphysics schemes from
1368 00 UTC to 06 UTC on 20 May 2011. Right axes are heights in km; horizontal
1369 dashed lines indicate the level of the 0 °C environmental temperature.

1370 Figure 10 PDF matching scores for the CFADs in Figure 9. The score indicates the
1371 amount of overlap between the simulated and observed PDF at each level.

1372 Figure 11 Components of the 4ICE radar reflectivity CFAD shown in Figure 9 (d) due
1373 to (a) rain, (b) snow, (c) graupel and (d) hail. Horizontal dashed lines indicate
1374 the level of the 0 °C environmental temperature.

1375 Figure 12 Vertical cross-section of NEXRAD radar reflectivity at 10 UTC on 20 May
1376 2011. Positions of the cross-sections are shown by the lines in Figure 2 for
1377 the radar observations and WRF simulations, respectively.

1378 Figure 13 Top panel same as Figure 12, but for the NU-WRF Graupel simulation.
1379 Bottom panel shows the concurrent NU-WRF vertical velocity (colored
1380 contours), equivalent potential temperature (black contours), and virtual
1381 potential temperature (filled contours).

1382 Figure 14 Same as Figure 13 but for the NU-WRF Hail simulation.

1383 Figure 15 Same as Figure 13 but for the NU-WRF 4ICE simulation.

1384 Figure 16 Vertical velocity CFADs of in-cloud up- and downdrafts in the total,
1385 convective and stratiform regions.

1386 Figure A1 Hail mapping size thresholds as a function of hail mixing ratio and local in

cloud temperature. Hail mixing ratios less than the dashed line use a larger intercept (i.e., 0.240 cm^{-4}) representative of smaller hail while those greater than the solid line use a smaller intercept (i.e., 0.0048 cm^{-4}) representative of larger hail at each given temperature. Intercept values are interpolated for mixing ratios between the two thresholds.

Figure A2 Same as the top panel in Figure 15 except for the previous 4ICE scheme [Lang et al. 2014]. Horizontal composite reflectivity and stratiform separation are shown in the top two panels.

Figure A3 Same as Figure A2 but for the current 4ICE scheme.

Figure A4 Same as Figure 10 except with the previous 4ICE scheme [4ICE_v0, Lang et al., 2014] added.

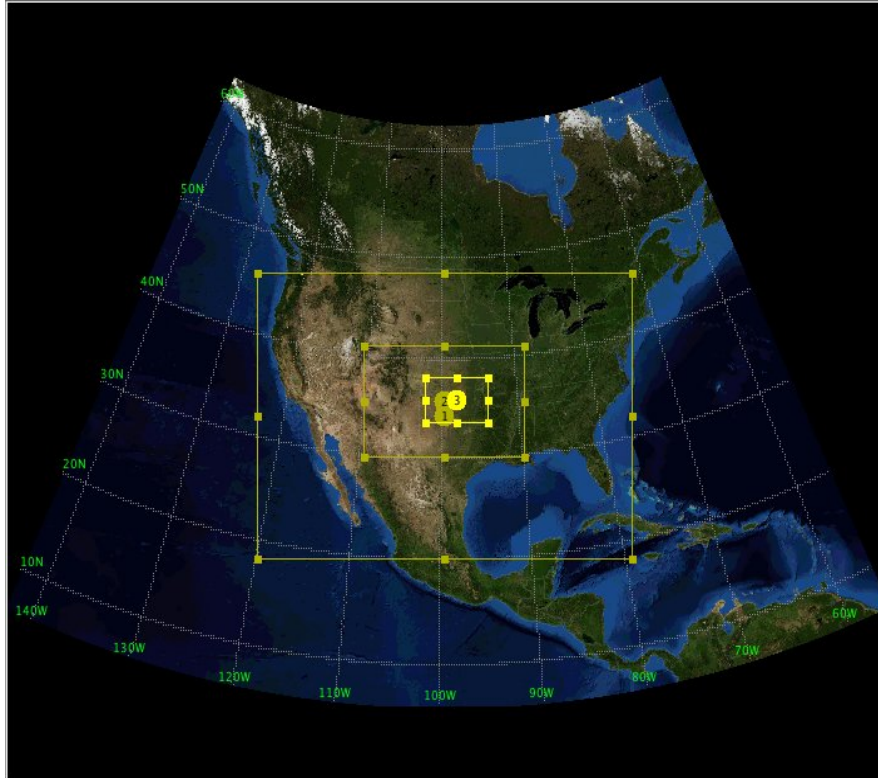
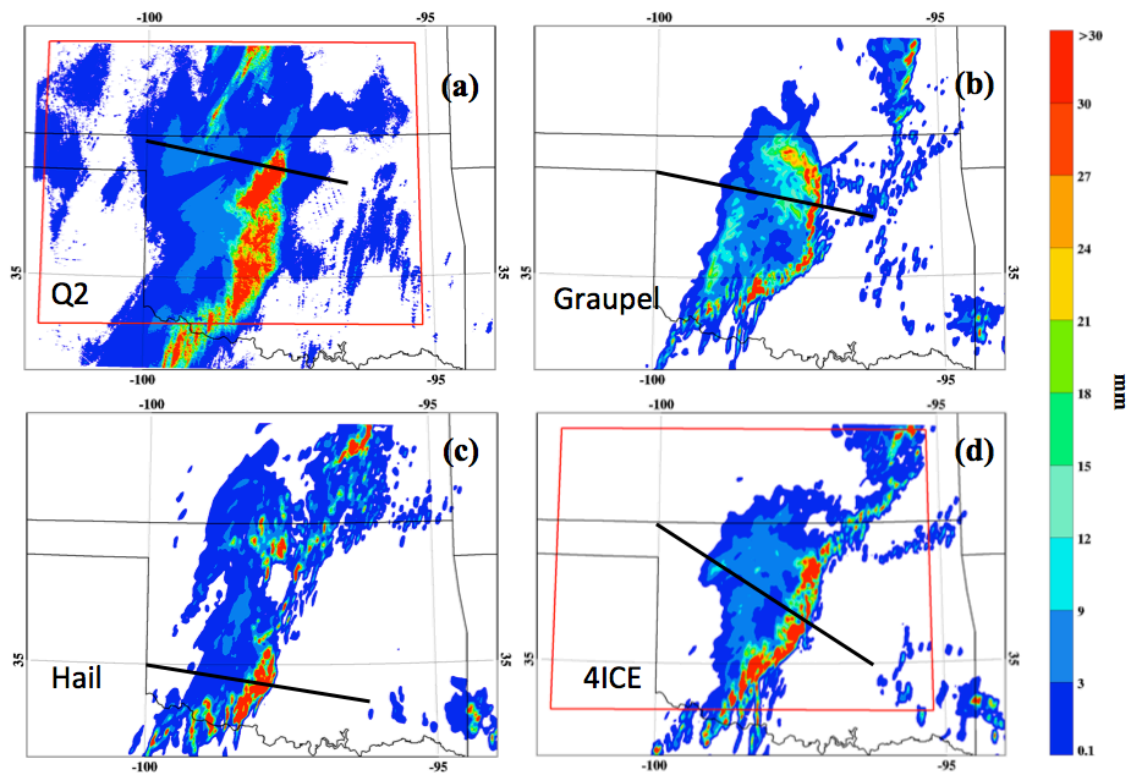


Figure 2 NU-WRF grid configuration. The outer domain (labeled 1 at the center) has a horizontal resolution of 9 km. The middle domain (labeled 2) has a horizontal resolution of 3 km, and the inner domain (labeled 3) has a horizontal resolution of 1 km and covers the southern Plains.

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1412

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1415 May 2011. The precipitation analysis area is indicated by the red boundary.

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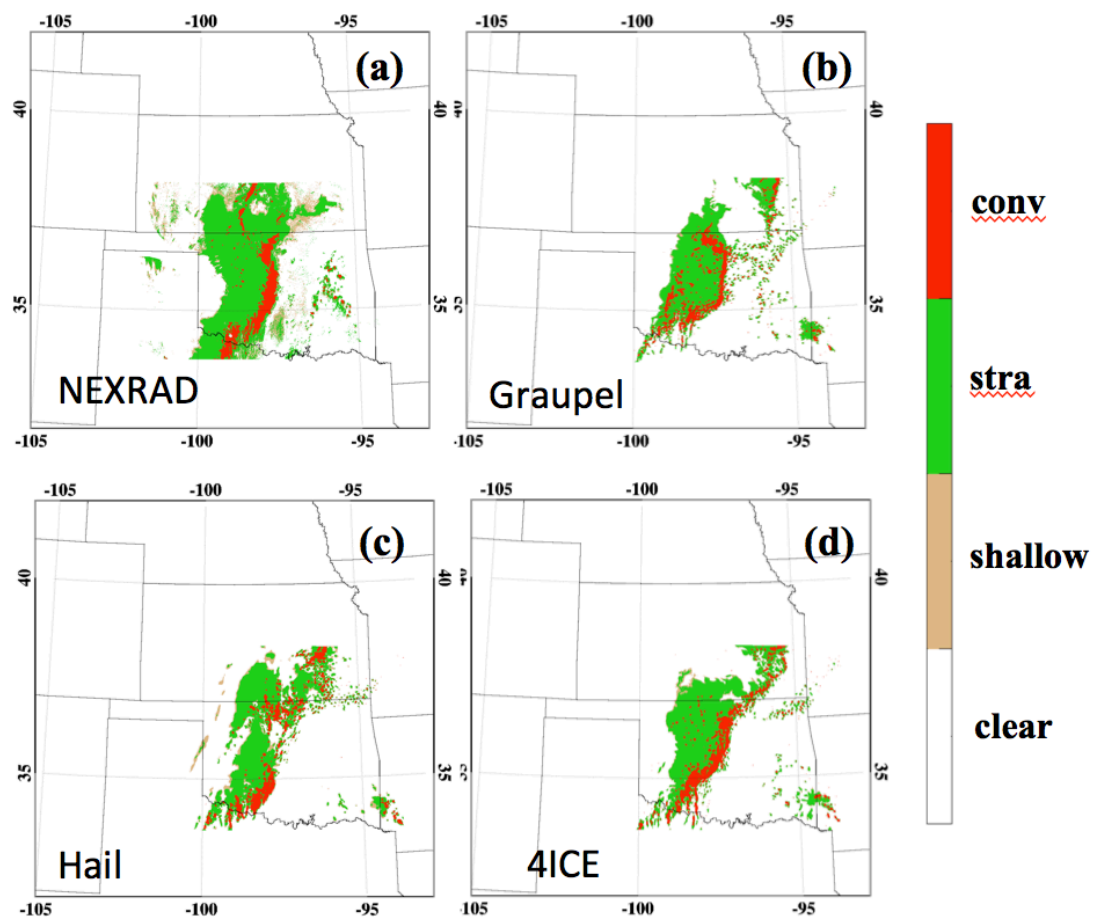


Figure 3 Observed and NU-WRF simulated convective and stratiform areas at 10 UTC on 20 May 2011. Red indicates convective regions and green stratiform regions.

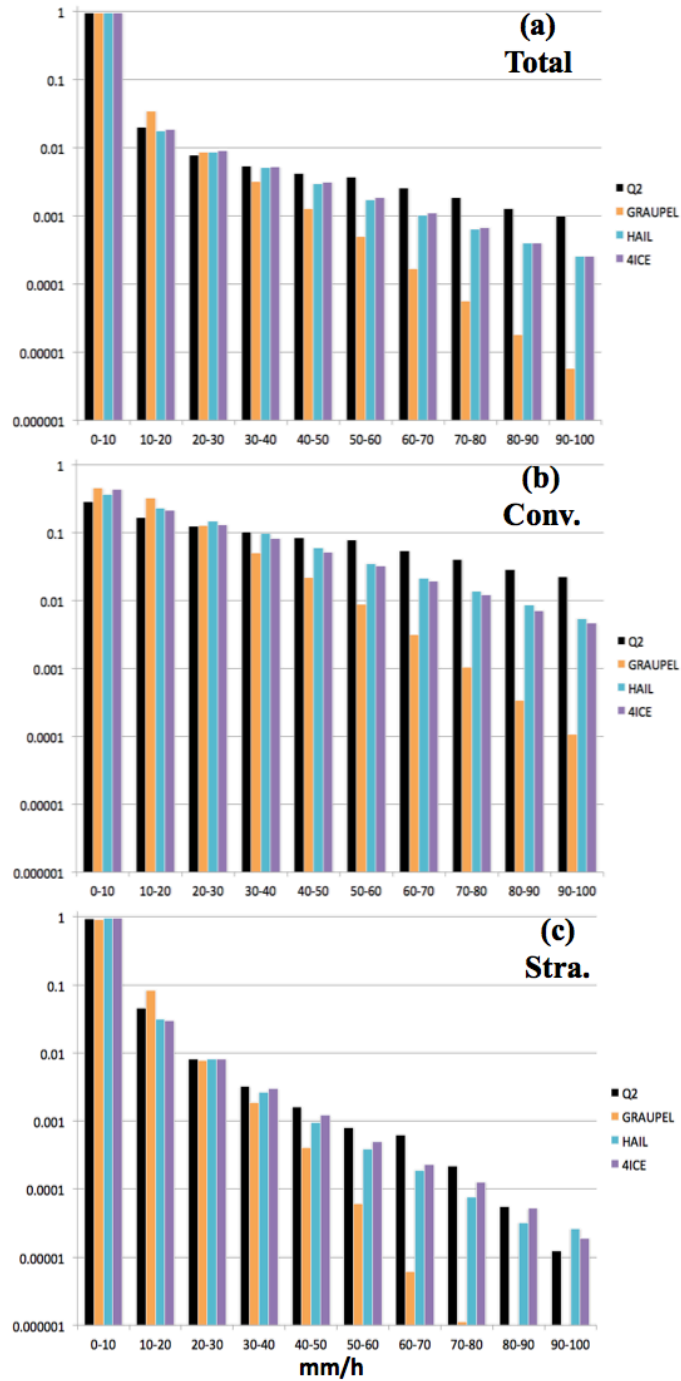


Figure 4 PDFs (probability distribution functions) of observed and NU-WRF simulated rainfall intensity in mm h⁻¹ from the three different Goddard microphysical schemes for the (a) total, (b) convective, and (c) stratiform regions. The observed rain rates are from Q2. PDFs were calculated every 10 minutes from

1438 both observed and simulated datasets from 06 UTC to 12 UTC on 20 May
1439 2011 within the analysis domains shown in Figure 2.

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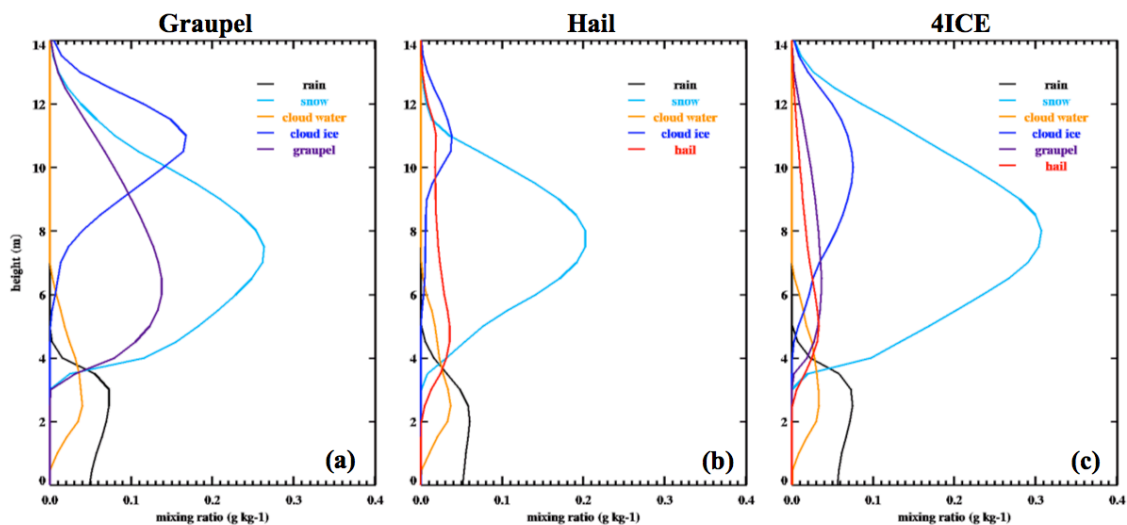
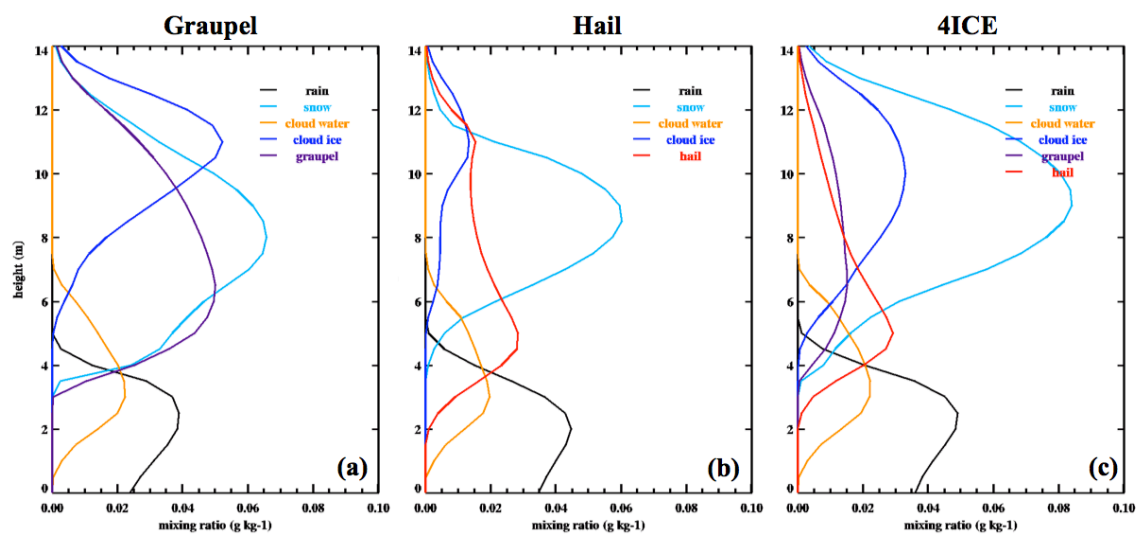


Figure 5 Hydrometeor profiles from the (a) Graupel, (b) Hail, and (c) 4ICE schemes from 06 UTC to 12 UTC on 20 May 2011.

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Figure 6 Same as Figure 5 except for the convective regions.

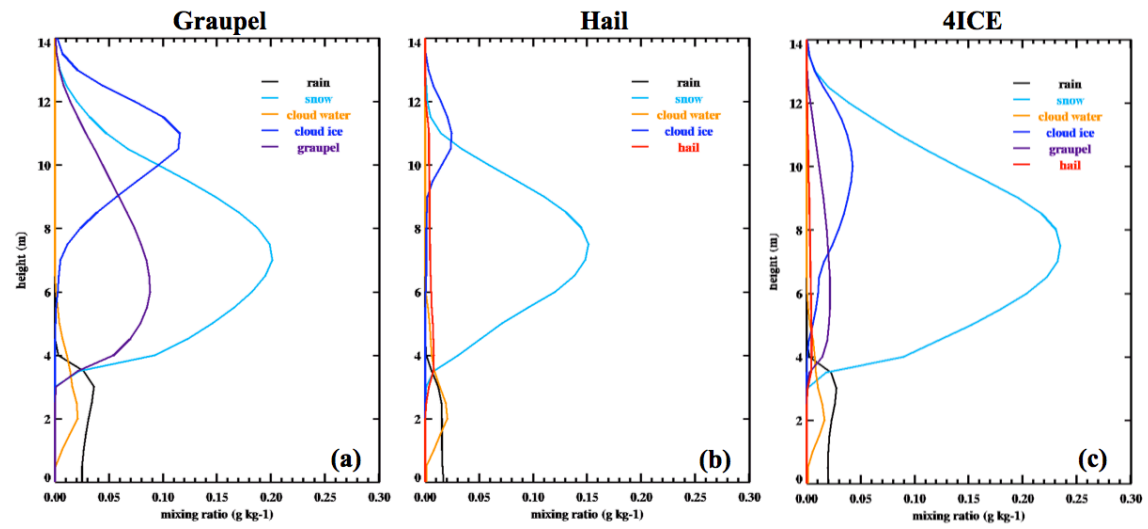
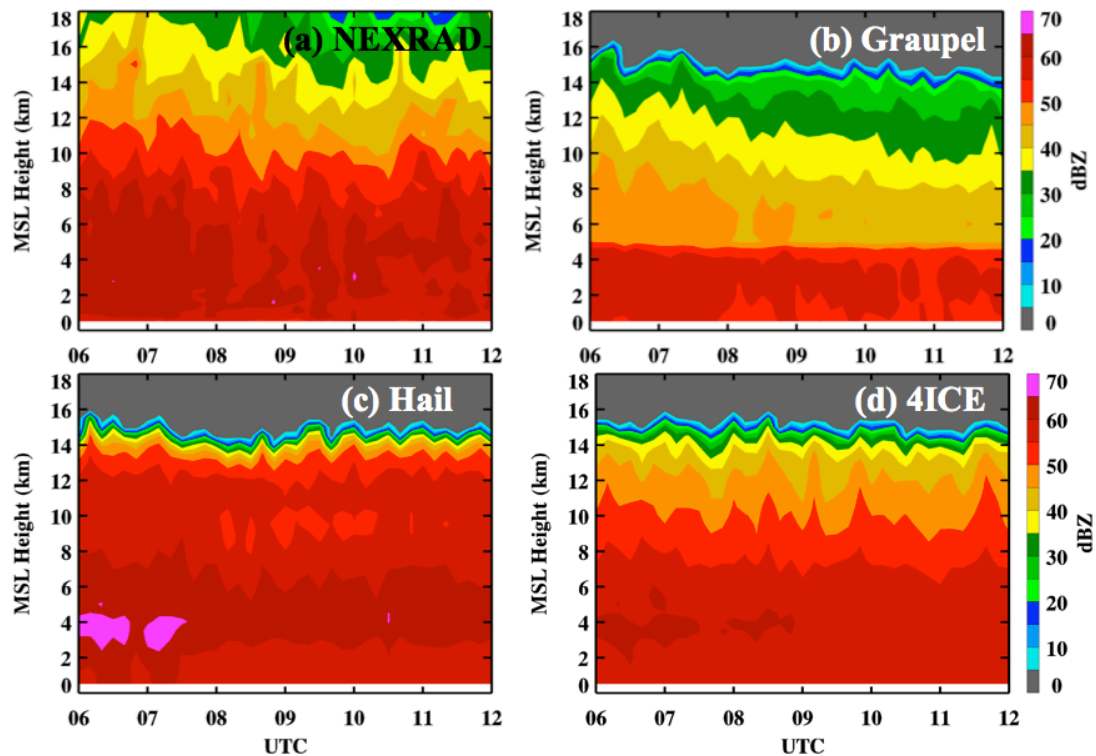


Figure 7 Same as Figure 5 except for the stratiform regions.

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1474 Figure 8 Maximum radar reflectivities for (a) NEXRAD observations and NU-WRF
1475 simulations with the (b) Graupel, (c) Hail, (d) 4ICE microphysics schemes.
1476 Right axes are heights in km, while horizontal lines show the time range from
1477 00 UTC to 12 UTC on 20 May 2011.

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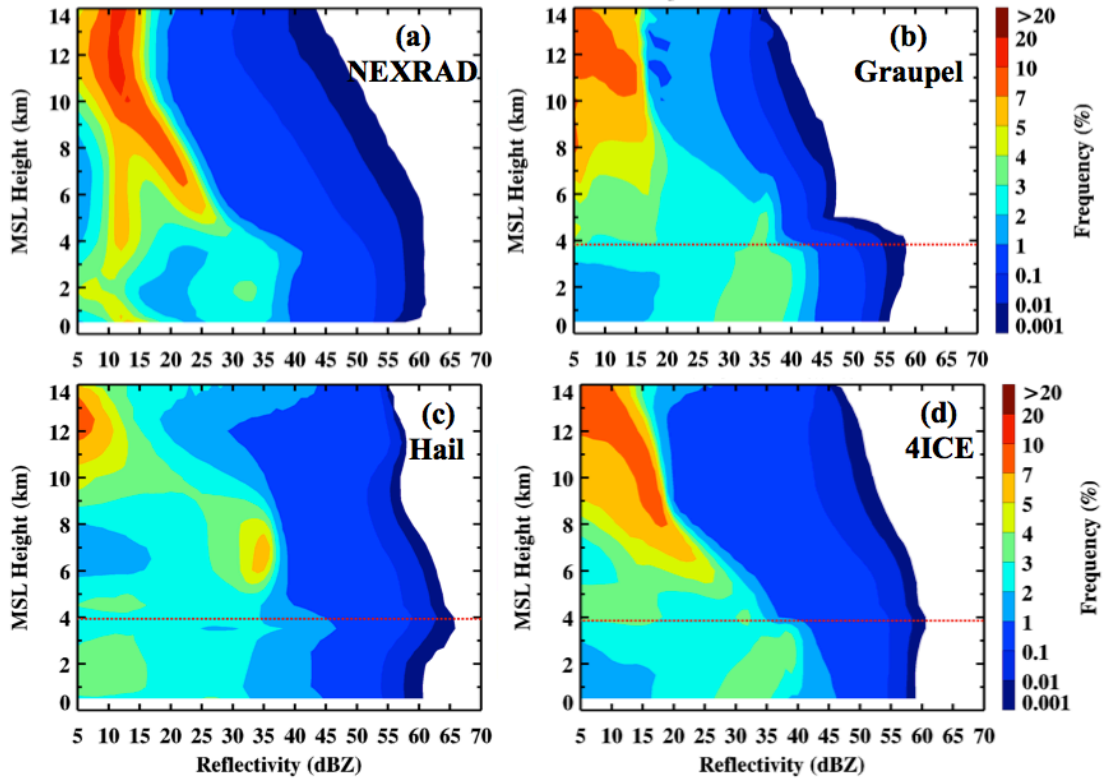
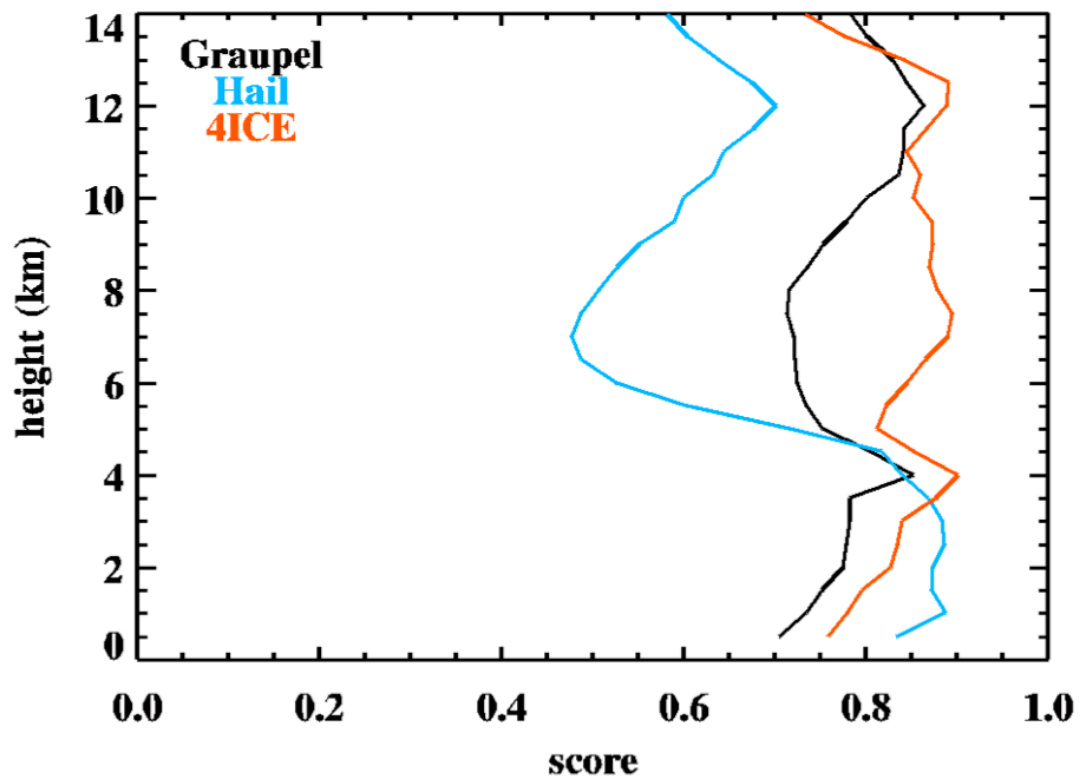


Figure 9 Radar reflectivity CFADs from (a) NEXRAD observations and NU-WRF simulations with the (b) Graupel, (c) Hail, (d) 4ICE microphysics schemes from 00 UTC to 06 UTC on 20 May 2011. Right axes are heights in km; horizontal dashed lines indicate the level of the 0 °C environmental temperature.

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1497 Figure 10 PDF matching scores for the CFADs in Figure 9. The score indicates the
1498 amount of overlap between the simulated and observed PDF at each level.

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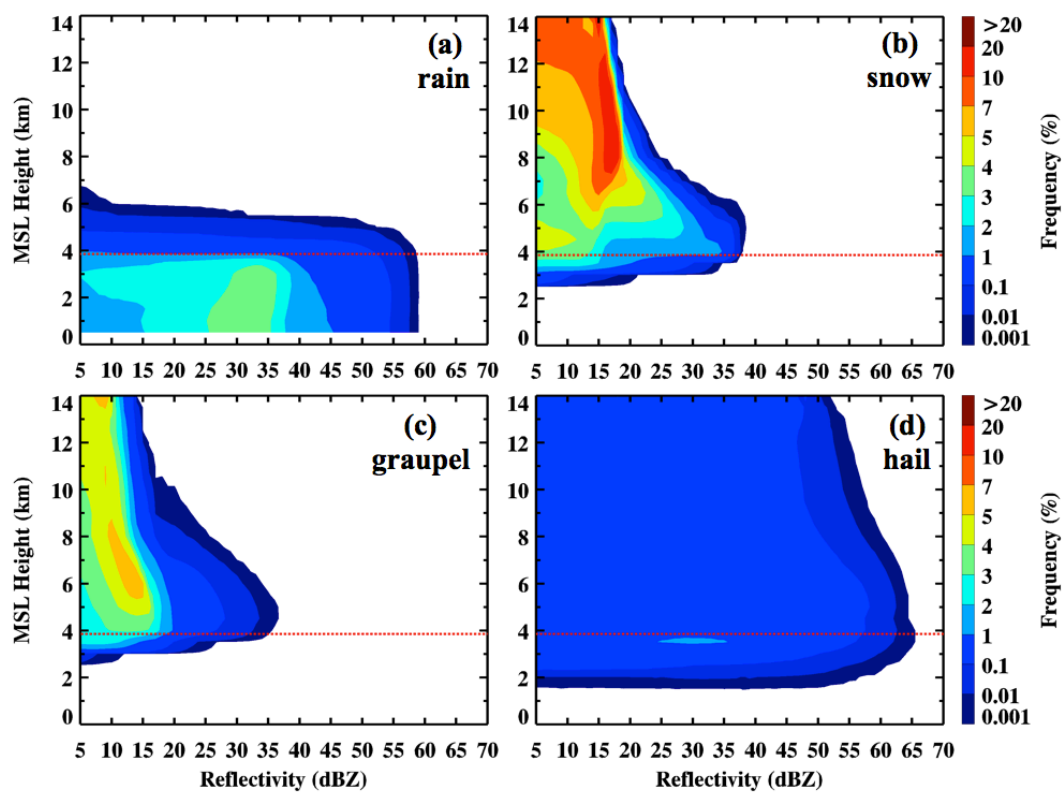
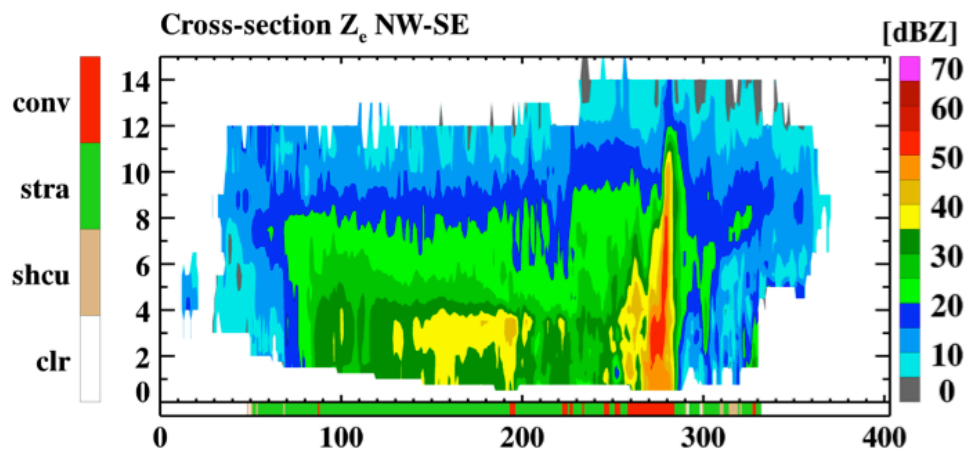


Figure 11 Components of the 4ICE radar reflectivity CFAD shown in Figure 9 (d) due to (a) rain, (b) snow, (c) graupel and (d) hail. Horizontal dashed lines indicate the level of the 0 °C environmental temperature.

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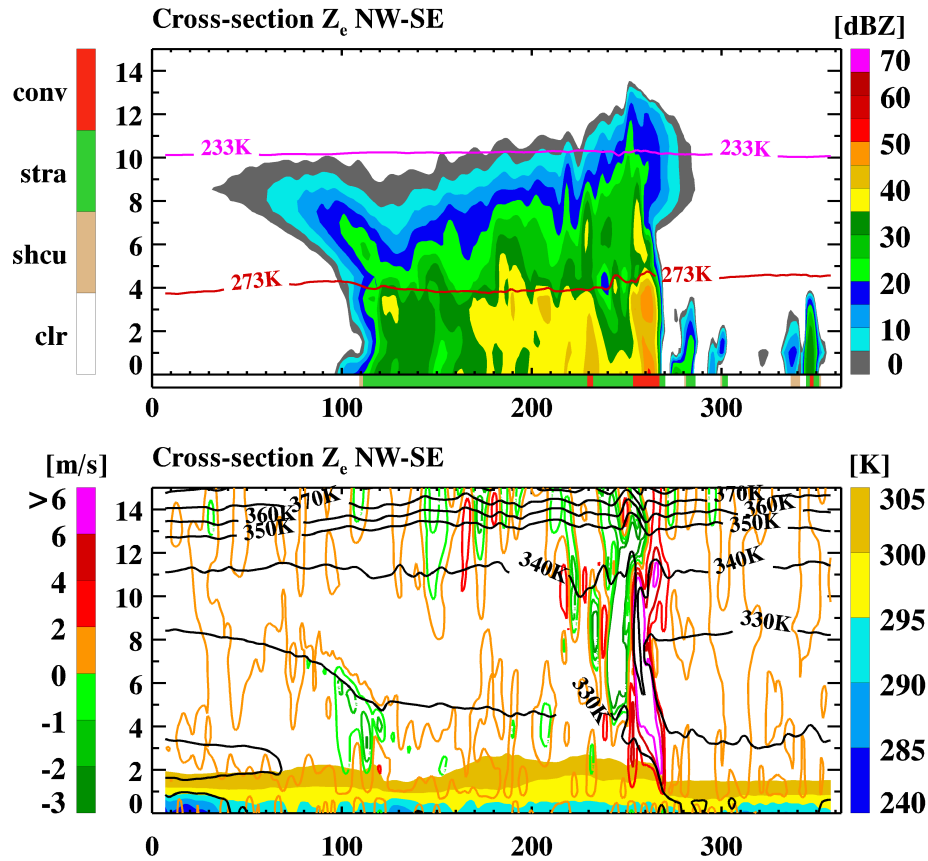
1520 Figure 12 Vertical cross-section of NEXRAD radar reflectivity at 10 UTC on 20 May

1521 2011. Positions of the cross-sections are shown by the lines in Figure 2 for

1522 the radar observations and WRF simulations, respectively.

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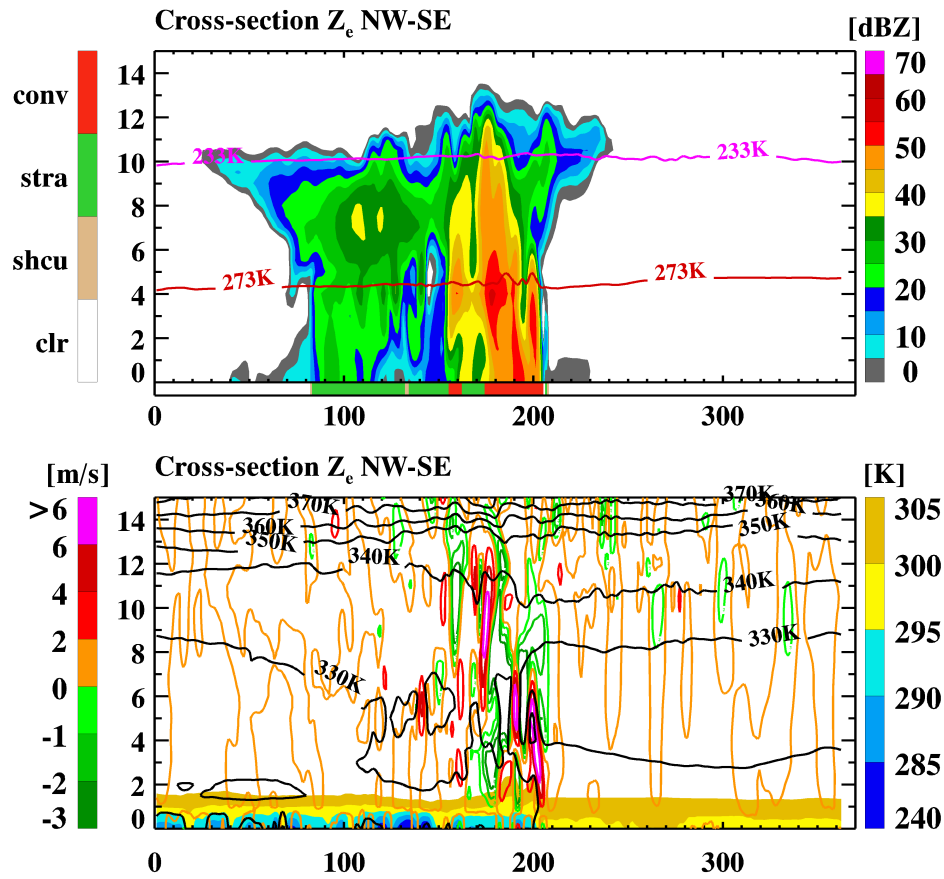
1526 Figure 13 Top panel same as Figure 12, but for the NU-WRF Graupel simulation.

1527 Bottom panel shows the concurrent NU-WRF vertical velocity (colored

1528 contours), equivalent potential temperature (black contours), and virtual

1529 potential temperature (filled contours).

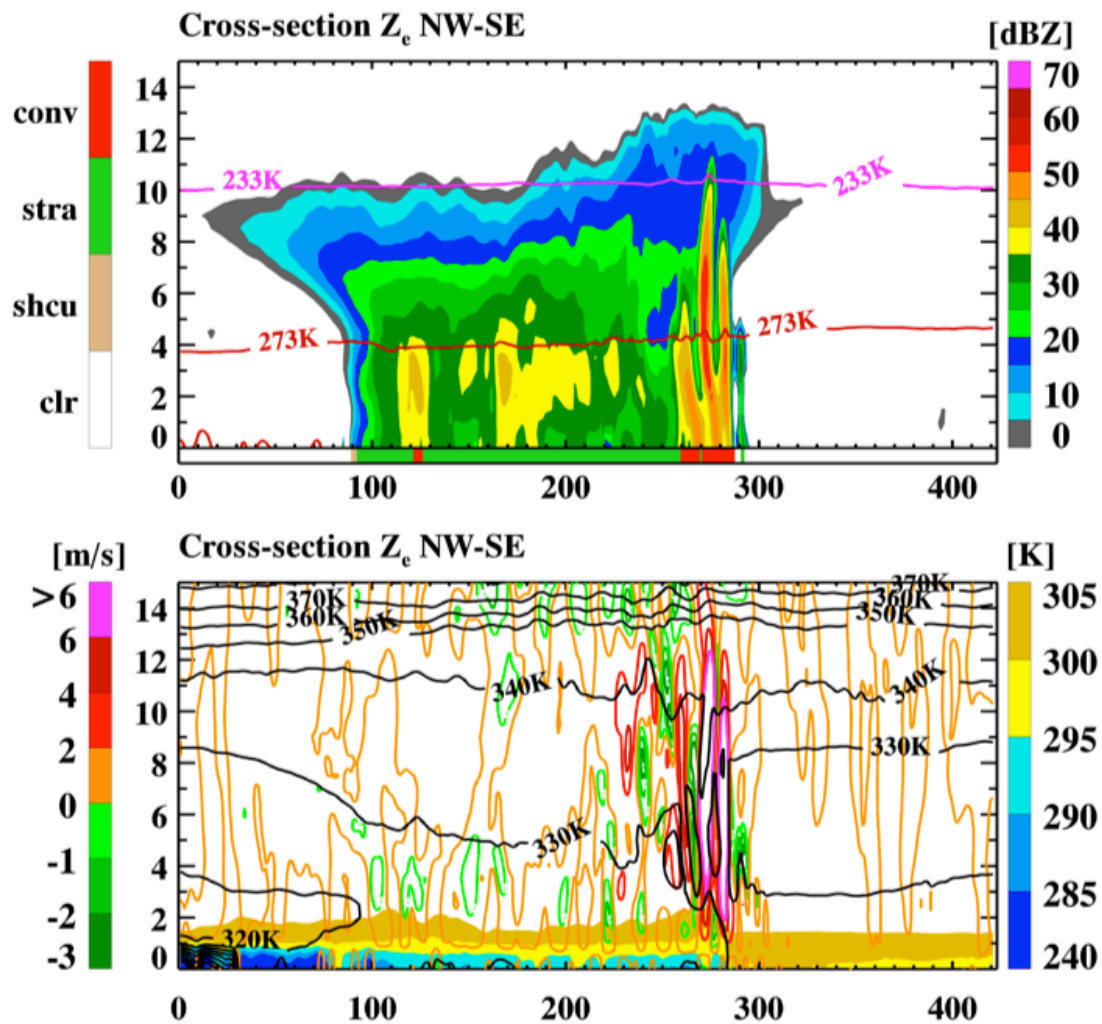
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1532 Figure 14 Same as Figure 13 but for the NU-WRF Hail simulation.

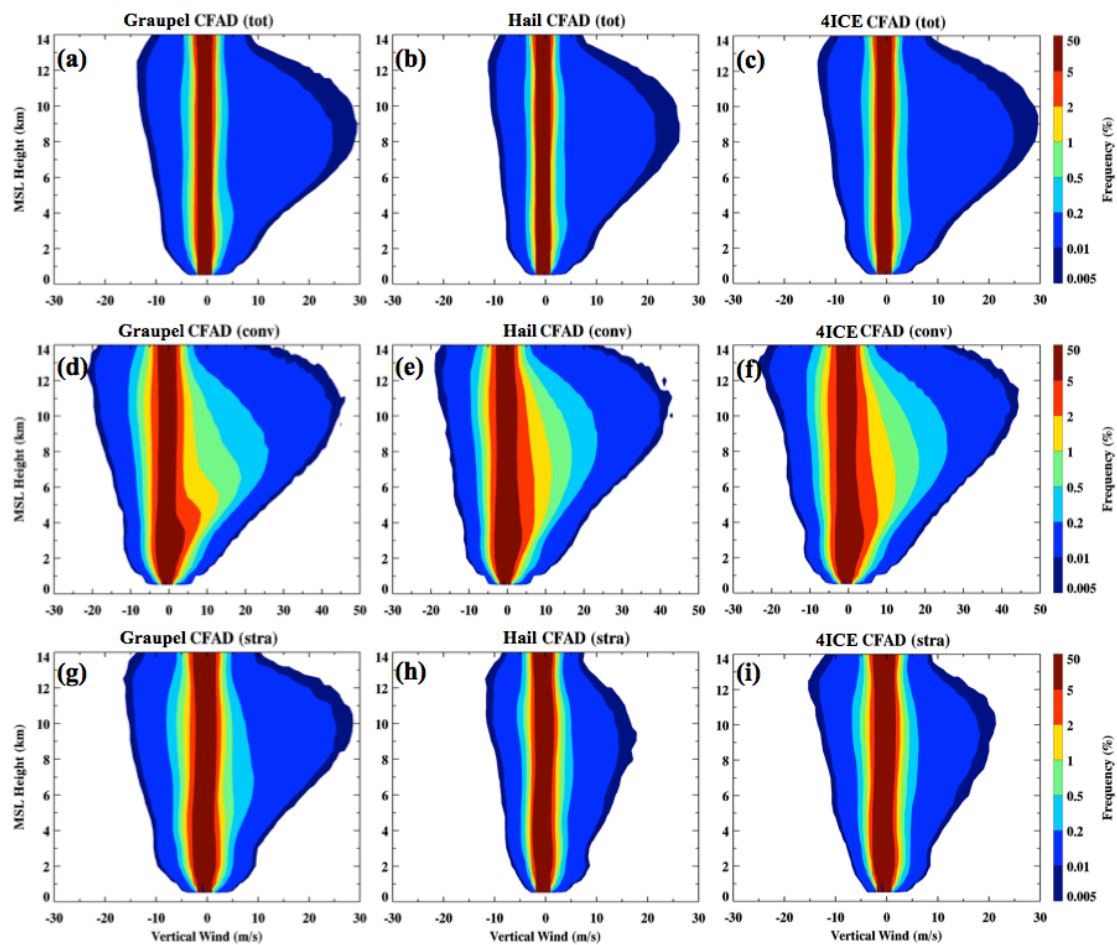
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1535 Figure 15 Same as Figure 13 but for the NU-WRF 4ICE simulation.

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1538 Figure 16 Vertical velocity CFADs of in-cloud up- and downdrafts in the total,
 1539 convective and stratiform regions.

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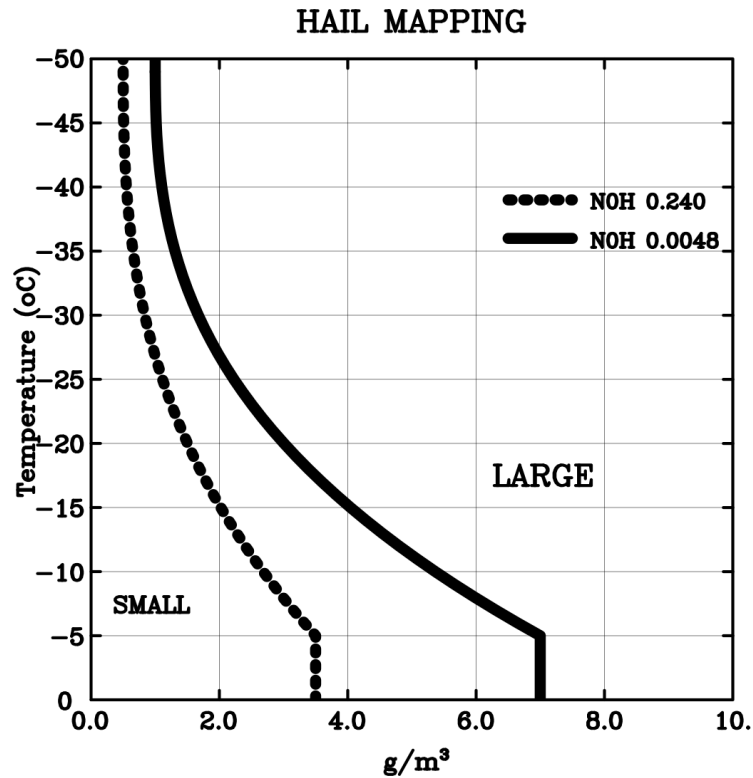
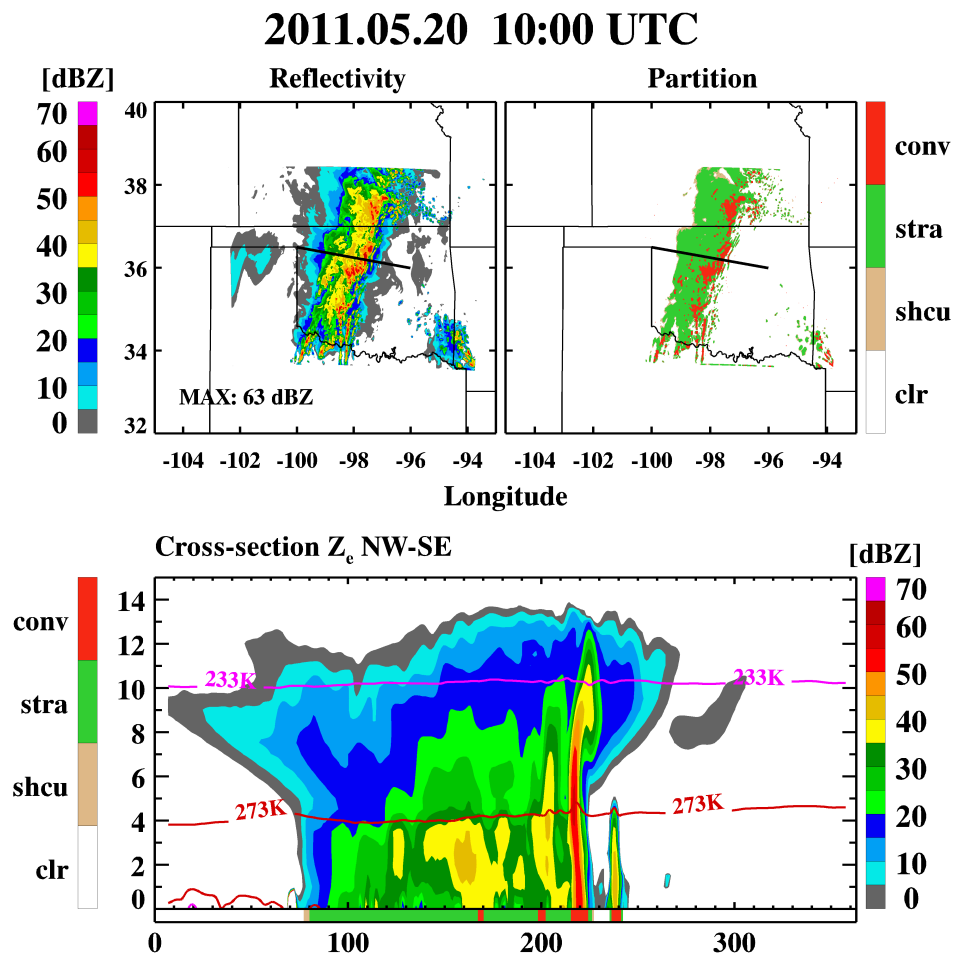


Figure A1 Hail mapping size thresholds as a function of hail mixing ratio and local in cloud temperature. Hail mixing ratios less than the dashed line use a larger intercept (i.e., 0.240 cm^{-4}) representative of smaller hail while those greater than the solid line use a smaller intercept (i.e., 0.0048 cm^{-4}) representative of larger hail at each given temperature. Intercept values are interpolated for mixing ratios between the two thresholds.

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1563 Figure A2 Same as the top panel in Figure 15 except for the previous 4ICE scheme

1564 [Lang et al. 2014]. Horizontal composite reflectivity and stratiform separation

1565 are shown in the top two panels.

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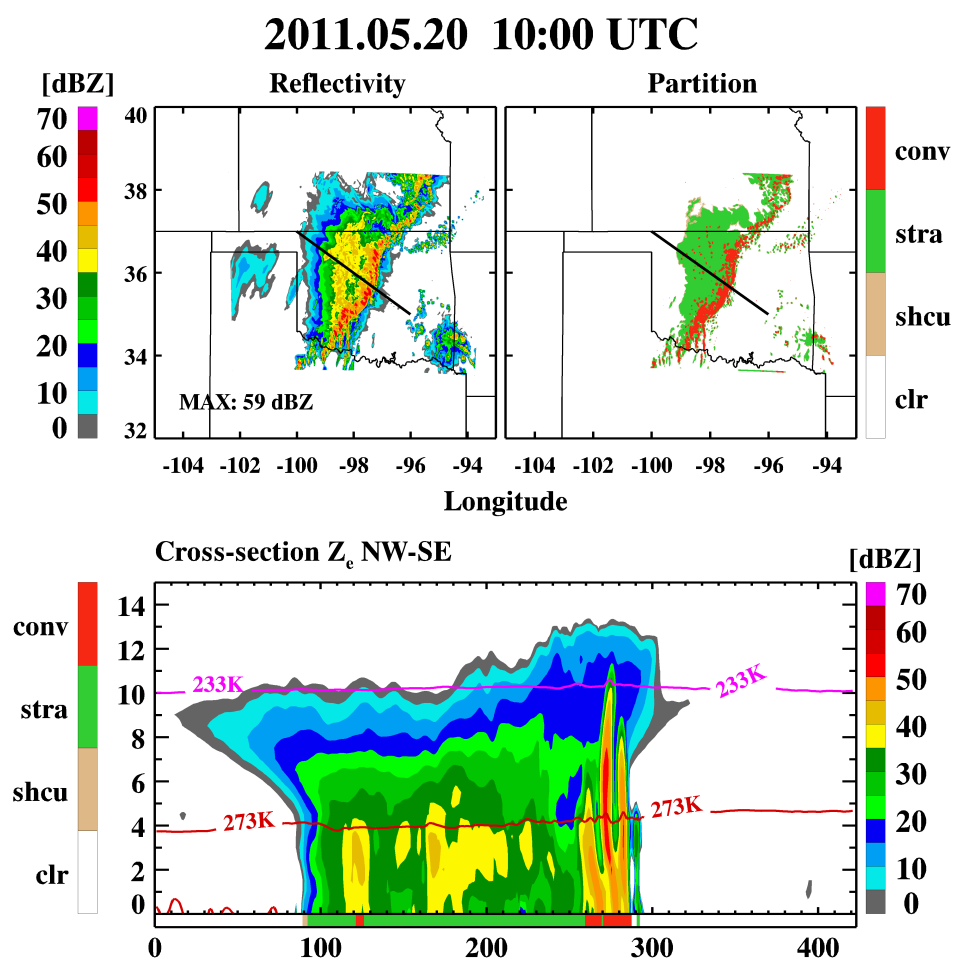
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1576 Figure A3 Same as Figure A2 but for the current 4ICE scheme.

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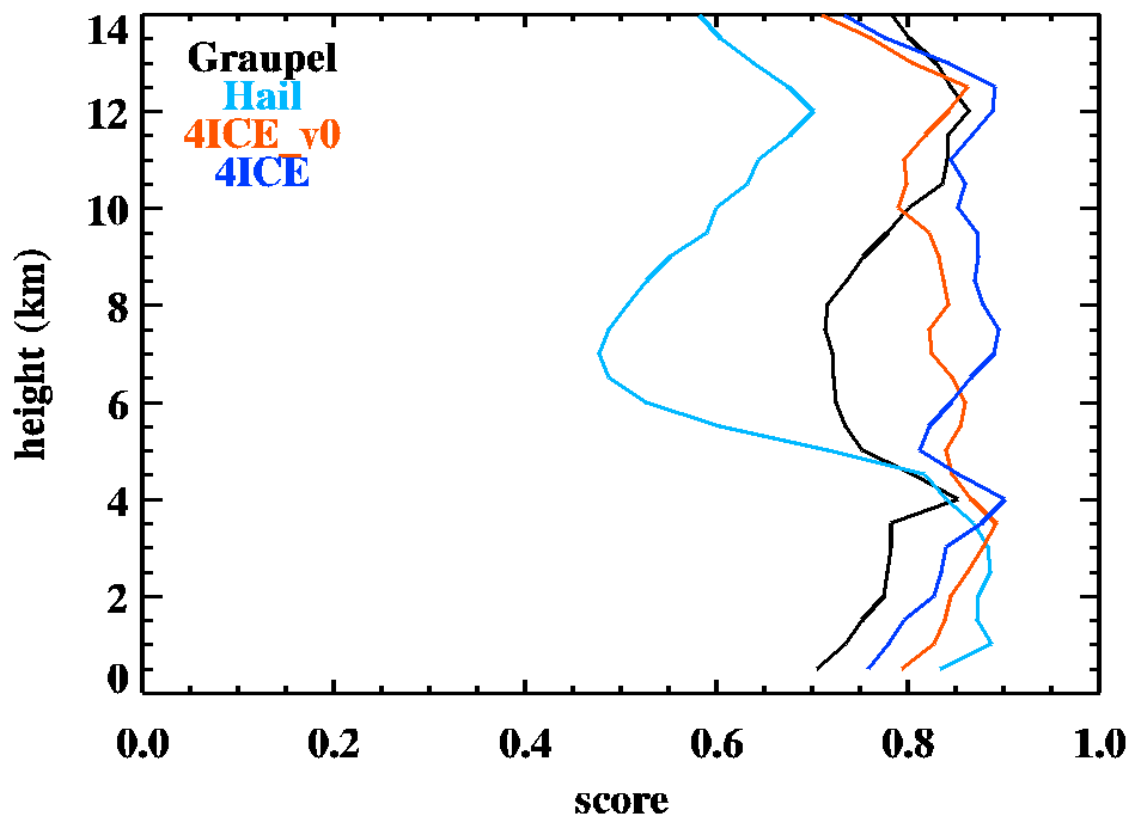


Figure A4 Same as Figure 10 except with the previous 4ICE scheme [4ICE_v0, Lang et al., 2014] added.